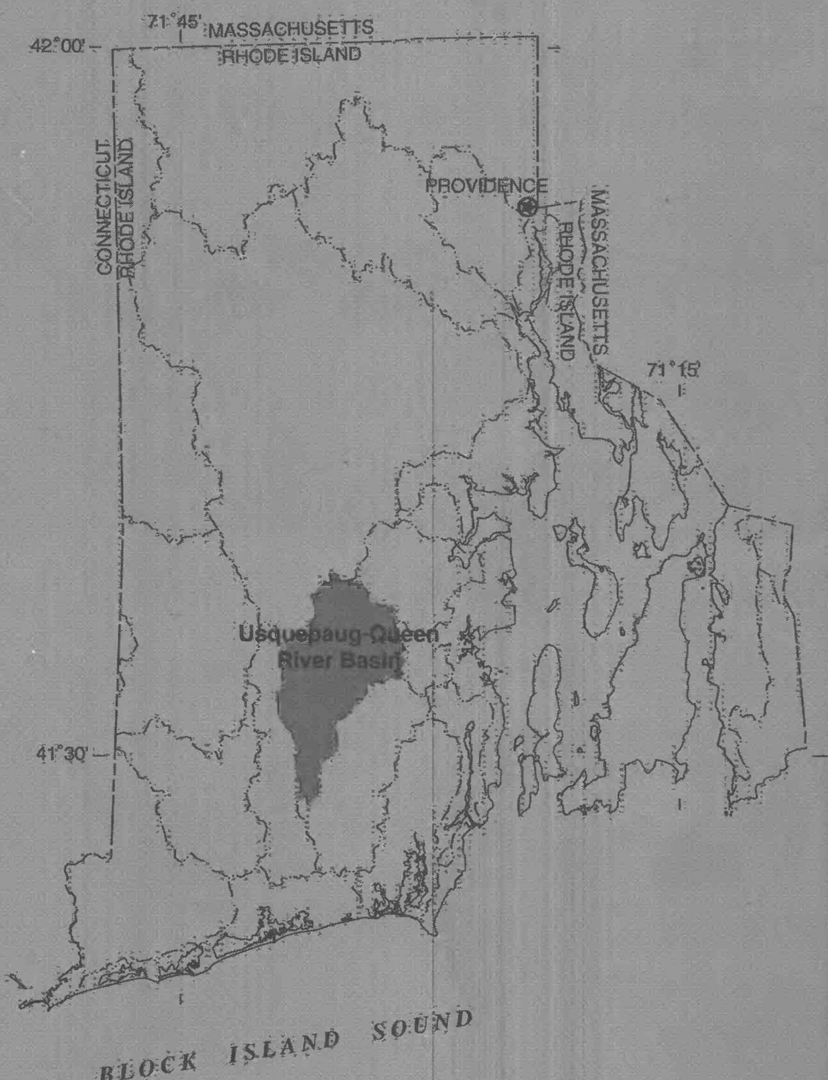
Hydrogeology, Water Quality, and Simulation of Ground-Water-Development Alternatives in the Usquepaug-Queen Ground-Water Reservoir, Southern Rhode Island

U.S. Geological Survey
Water-Resources Investigations Report 97-4126



Prepared in cooperation with the
RHODE ISLAND WATER RESOURCES BOARD

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By DAVID C. DICKERMAN, JOHN D. KLIEVER, and
JANET RADWAY STONE

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Providence, Rhode Island
1997

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CONVERSION FACTORS

Multiply	By	To obtain
acre	0.4047	hectare
cubic foot (ft^3)	0.02832	cubic meter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per second per square mile [$(ft^3/s)/mi^2$]	0.01093	cubic meter per second per square kilometer
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
gallon (gal)	3.785	liter
gallon per minute (gal/min)	0.06309	liter per second
inch (in.)	25.4	millimeter
mile (mi)	1.609	kilometer
million gallons per day (Mgal/d)	0.04381	cubic meter per second
square foot per day (ft^2/d)	0.09290	square meter per day
square mile (mi^2)	2.590	square kilometer

Temperature in degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) as follows:

°F = 1.8 (°C) + 32.

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.

ABBREVIATED WATER-QUALITY UNITS USED IN THIS REPORT:

Chemical concentrations and selected physical properties are given in metric units. Chemical concentration is given in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Milligrams per liter is a unit expressing the concentration of chemical constituents in solution as weight (milligrams) of solute per unit volume (liter) of water.

One thousand micrograms per liter is equivalent to one milligram per liter.

For concentrations less than 7,000 mg/L, the numerical value is the same as for concentrations in parts per million.

Specific conductance of water is expressed in microsiemens per centimeter at 25 degrees Celsius (µS/cm). This unit is equivalent to micromhos per centimeter at 25 degrees Celsius (µmho/cm), formerly used by the U.S. Geological Survey.

Hydrogeology, Water Quality, and Simulation of Ground-Water-Development Alternatives in the Usquepaug-Queen Ground-Water Reservoir, Southern Rhode Island

By David C. Dickerman, John D. Kliever, *and* Janet Radway Stone

Abstract

The Usquepaug-Queen River Basin study describes the hydrogeology, water quality, and simulation of pumping from wells for selected ground-water-development alternatives in the ground-water reservoir under average (1975–90) and drought (1963–66) conditions. In general, ground-water quality is suitable for most purposes. The study provides an evaluation of the effects of simulated pumping of 4 to 11 million gallons per day of ground water on the stream-wetland-aquifer system.

Three principal geologic units underlie the Usquepaug-Queen River Basin—glacial stratified deposits (stratified drift), glacial till, and crystalline bedrock. Thick and extensive deposits of saturated coarse-grained stratified deposits form the major and most productive aquifer in the Usquepaug-Queen River Basin. The 36.1-square mile Usquepaug-Queen River Basin is in the Pawcatuck River Basin in southern Rhode Island. Stratified deposits cover about 42 percent of the basin and reach a maximum known thickness of 122 feet. The stratified deposits are subdivided into coarse-grained units (dominantly fine to very coarse sand and gravel) and fine-grained units (dominantly very fine sand, silt, and clay). Transmissivity is highest in coarse-grained stratified materials, which have the capability of yielding relatively high volumes of water to wells. Transmissivity is lowest in fine-grained stratified materials, which consist predominantly of lake-bottom deposits. Transmissivity of the stratified-drift aquifer ranges from 1,900 to 27,800 feet squared per day, and horizontal hydraulic conductivity ranges from 25 to 470 feet per day. The stratified-drift aquifer is the only aquifer in the Usquepaug-Queen River Basin capable of producing yields of 0.5 million gallons per day or more from individual wells. Pumping from ground-water and surface-water sources in the Usquepaug-Queen River Basin averaged 0.28 million gallons per day during 1989 and 0.48 million gallons per day during 1990.

Ground water and surface water (which is primarily ground-water runoff) in the Usquepaug-Queen River Basin are suitable for most purposes on the basis of a comparison of physical properties and chemical constituents to drinking-water standards. Ground water in the basin is somewhat corrosive because of its low hydrogen-ion concentration. Specific conductance and concentrations of dissolved chloride and dissolved sodium are high in ground water in parts of the Usquepaug-Queen River Basin, which indicates the effects of highway de-icing salts on ground-water quality. Nitrogen (nitrite plus nitrate) concentrations in some localized areas exceed the U.S. Environmental Protection Agency maximum contaminant level of 10 milligrams per liter for drinking water.

The effects of selected ground-water-development alternatives on ground-water levels, wetland-water levels, and streamflow in the Usquepaug-Queen ground-water reservoir were evaluated by means of a three-layer ground-water-flow model. Development alternatives were

simulated for average annual (1975–90) and drought (1963–66) conditions. In general, higher simulated pumping rates produced greater drawdowns than lower pumping rates. Drawdowns generally can be reduced by distributing the total pumping over many wells; however, drawdowns were minimal (less than 1.3 feet) in well SNW 906, which was near a major stream (recharge boundary); and drawdowns were substantial (at least 12 feet) in well EXW 33, which was near the edge of the model aquifer boundary (barrier boundary). Total gains in flow from ground-water discharge for all streams in the model area were not affected by the location of wells; however, the amount of ground-water pumpage derived from induced infiltration of streamflow varies significantly. Water levels in the wetlands tend to be constant even during simulated pumping. In general, pumping during simulated drought conditions increased drawdowns fractionally and greatly reduced overall streamflow gains.

Pumping from the Usquepaug-Queen stratified-drift aquifer causes infiltration of streamflow along stream segments simulated in the ground-water-flow model. Results of simulations for average conditions show that from 56 to 75 percent of the total water pumped is derived from intercepted ground-water runoff and that the amount of well water derived from induced recharge of streamflow ranged from 20 to 39 percent. The areal extent of contributing areas for selected simulated pumping wells suggest that large areas of stratified drift may need to be protected from land-use practices that are incompatible with the development of potable ground water in the Usquepaug-Queen ground-water reservoir.

INTRODUCTION

The Usquepaug-Queen ground-water reservoir is one of nine major ground-water reservoirs in the Pawcatuck River Basin (fig. 1) in which the Rhode Island Water Resources Board (RIWRB) needs information on hydrogeology, water quality, and ground-water availability to fulfill its responsibility for implementing development of the State's major water resources. The Usquepaug-Queen ground-water reservoir is the fifth subbasin of the Pawcatuck River to be studied as part of a cooperative program between the U.S. Geological Survey (USGS) and the RIWRB to assess ground-water resources in southern Rhode Island. The RIWRB supports the simulation of ground-water-development alternatives as an effective tool that can assist water-resource planners in attaining the goal of minimizing the effects of pumping from wells on ground-water levels, wetland water levels, and streamflow.

Rhode Island's major **aquifers**[1] are typically in glacial **stratified deposits** (also **stratified drift**), which are present primarily in stream valleys. Where the **transmissivity** and **saturated thickness** of these aquifers are greatest, ground water may be present in quantities suitable for development and large-volume use; such aquifers are termed **ground-water reservoirs**. The Usquepaug-Queen ground-water reservoir underlies an area of about 8 mi^2 in the valleys drained primarily by Fisherville Brook and the Queen and Usquepaug Rivers upstream from the USGS streamflow-**gaging station** on the Usquepaug River near Usquepaug (fig. 1).

Purpose and Scope

This report describes the hydrogeology, current water quality, and ground-water development alternatives in the Usquepaug-Queen ground-water reservoir in southern Rhode Island. The report includes a discussion of the: (1) geology; (2) surface water; (3) hydraulic properties of and recharge to the stratified-drift aquifer; (4) water use; (5) present chemical quality of surface water, derived primarily from ground-water runoff, and ground water; (6) input to and calibration of a ground-water-flow model; (7) effect of ground-water development alternatives on ground-water levels, streamflow, and wetlands; (8) stream-wetland-aquifer interaction; and (9) delineation of contributing areas for selected simulated pumping wells.

[1]Boldface terms in text are defined in the glossary.

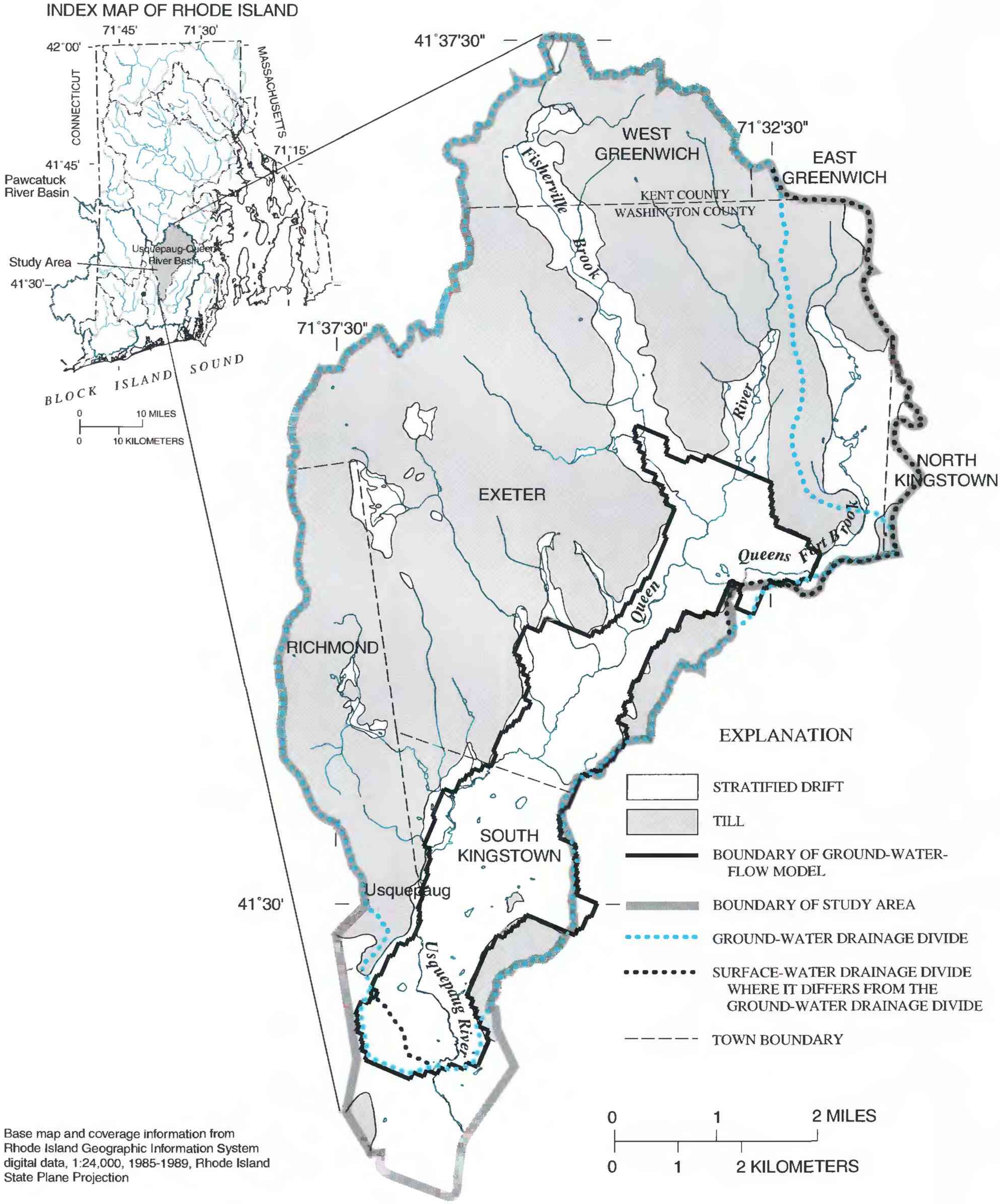


Figure 1. Location, generalized hydrogeology, and area represented by the ground-water model of the Usquepaug-Queen River Basin, southern Rhode Island.

Approach

The stream-wetland-aquifer system consists primarily of the Usquepaug and Queen Rivers and the stratified-drift aquifer. Pumpage in selected wells in the Usquepaug-Queen ground-water reservoir were simulated with the ground-water-flow model to determine the potential for the stratified-drift aquifer to yield 0.5 Mgal/d or more to individual wells. A **numerical model** was used to simulate different ground-water-development alternatives. The area of the ground-water-flow model shown in figure 1 approximates the area of the Usquepaug-Queen ground-water reservoir.

Data from 275 ground-water sites, **lithologic logs** from 64 test holes, seismic-refraction data from 9 **seismic refraction** lines, **aquifer tests** at 4 sites (Allen and others, 1963; Kliever, 1995), 4 geologic sections, and a geologic materials map were used to characterize the hydrogeology of the Usquepaug-Queen ground-water reservoir. Monthly water-level data from 32 observation wells were used to determine average water-table conditions throughout the Usquepaug-Queen River Basin for 1975–90. Water samples were collected from 17 surface-water sites and 34 wells to assess the quality of surface and ground water. Data from nine partial-record stations were used to estimate streamflow; these data were needed for calibration of a three-layer ground-water-flow model of the stream-wetland-aquifer system. The ground-water-flow code MODFLOWP (Hill, 1992) was used to construct the model, which was then used to evaluate the effects of simulated ground-water pumping on ground-water levels, streamflow, and wetlands for 11 development alternatives in the stratified-drift stream-wetland-aquifer system. The particle-tracking algorithm MODPATH (Pollock, 1994) was used in conjunction with the results of the ground-water-flow model to estimate contributing area to selected pumped wells.

Previous Studies

Hydrogeologic information is available from earlier studies that include part or all of the Usquepaug-Queen River Basin. Reconnaissance studies on the availability of ground water were done by Bierschenk (1956), Hahn (1959), and Lang (1961). A comprehensive quantitative study on the availability of ground water in the upper Pawcatuck River Basin, which includes the Usquepaug-Queen ground-water reservoir, was completed by Allen and others (1966). The hydrogeologic interpretations in this report were based on data collected during 1988–92 for this study (Kliever, 1995), and supplemented with data collected during 1957–60 in the upper Pawcatuck River Basin (Allen and others, 1963).

Additional data for the Usquepaug-Queen ground-water reservoir area have been collected as part of the ongoing USGS statewide hydrologic data networks. Data from these networks are published in annual reports of the U.S. Geological Survey (1940–50, 1951–60, 1961–64, 1965–74, and since 1975). These data include records of **discharge** (1959–60, and 1975–90) of the Usquepaug River near Usquepaug, R.I., and records of water-level fluctuations (1955–90) in observation well SNW 515.

Surficial geology has been mapped at a scale of 1:31,680 for the Slocum quadrangle (Power, 1957) and at a scale of 1:24,000 for the Kingston quadrangle (Kaye, 1960). The bedrock geology has been mapped at a scale of 1:31,680 for the Slocum quadrangle (Power, 1959) and at a scale of 1:24,000 for the Kingston quadrangle (Moore, 1964). Bedrock geologic units have been updated and mapped at a regional scale of 1:100,000 on the Bedrock Geologic Map of Rhode Island (Hermes and others, 1994).

Description of Study Area

The Usquepaug-Queen River Basin (fig. 1) is in southern Rhode Island and includes parts of the towns of Exeter, East Greenwich, North Kingstown, Richmond, South Kingstown, and West Greenwich. Most of the Usquepaug-Queen River Basin is in Washington County, with a small area in Kent County. The area is part of the Seaboard Lowland section of the New England physiographic province (Fenneman, 1938, pl. 1).

The Usquepaug-Queen River Basin is characterized by gently rolling topography and the northeast-southwest trending valleys of the Queen and Usquepaug Rivers. The basin is about 90 to 95 percent forested. Altitudes range from 555 ft above sea level at the summit of Pine Hill near the northwest corner of the basin to 95 ft above sea level at the USGS streamflow gaging station on the Usquepaug River at the basin outlet (pl. 1). Maximum relief in the Usquepaug-Queen River Basin is therefore 460 ft.

The subsurface-**drainage area** (33 mi^2) of the Usquepaug-Queen River Basin is slightly smaller than the surface-drainage area (36.1 mi^2). Boundaries for surface-water and **ground-water drainage divide**s are shown in figure 1.

Acknowledgments

The authors express appreciation to area residents who allowed access to wells and streams on their property for the purpose of measuring water levels and stream discharges and to collect water samples. Special acknowledgment is made to William and Marty LaFarge, and the Rhode Island Audubon Society, who allowed access to their property for the purpose of drilling test wells, installing observation wells, or to monitor existing wells.

HYDROGEOLOGY

Geology

Three principal geologic units underlie the Usquepaug-Queen River Basin—glacial stratified deposits, glacial **till**, and **crystalline bedrock**; these units have significantly different hydraulic characteristics. Crystalline bedrock is consolidated lithified rock with extremely low **primary porosity**; ground water flows along local, secondary fractures and joints in the **bedrock**. Till and stratified drift are unconsolidated glacial sediments that overlie the bedrock. Stratified deposits are further subdivided on the basis of texture into coarse-grained units (dominantly fine to very coarse sand and gravel) and fine-grained units (dominantly very fine sand, silt, and clay). Postglacial alluvium and swamp deposits locally overlie glacial deposits. A surficial geologic materials map and geologic sections showing textural units in the stratified drift in the Usquepaug-Queen River valley is shown on plate 1.

The **drainage basin** is underlain by igneous and metamorphic (crystalline) bedrock of Late Proterozoic and Paleozoic age; rock types are predominantly **granite** and granite **gneiss**. The Usquepaug-Queen River valley trends northeast-southwest and lies along the boundary between older (Late Proterozoic), more metamorphosed, granite gneisses of the Esmond igneous suite to the southeast, and younger (Devonian), less metamorphosed, granitic rocks of the Scituate igneous suite to the northwest (Hermes and others, 1994). Structural differences between the rock units can be seen in the topography of the area; ridges within the granitic rocks on the northwest side of the valley trend predominantly north to north-northwest and those within the granite gneiss area on the southeast side trend northeasterly. The presence of the bedrock valley beneath the Usquepaug-Queen River is due to structural and/or lithologic weakness in the bedrock along this northeast-southwest trending zone that caused the rock to be less-resistant to weathering and subsequent fluvial and glacial erosion. The position of this valley may reflect the presence of a northeast-southwest trending fault zone in the area to the southwest (Hermes and others, 1994).

Glacial till generally is a compact, nonsorted mixture of sand, silt, clay and stones ranging from a few to as much as 60 ft in thickness and blankets the bedrock surface in most places. Till deposits shown on plate 1 include tills of several different types and ages. Glacial tills laid down during two separate episodes of continental glaciation are present throughout southern New England, and both are locally present in the Usquepaug-Queen River Basin. The lower (older) till is discontinuous and generally is present only in areas of thick till accumulation, in drumlins, and on the northwest sides of bedrock hills. Lower till is typically a gray to olive-gray, very compact mixture of pebbles, cobbles, and few boulders in a sandy matrix that contains as much as 30 to 40 percent silt and clay; it is commonly stained with iron oxide. The upper part of lower till sections contain distinct subhorizontal **fissility**; this fissility and a less well-developed, subvertical, iron- and manganese-stained joint system give the lower till an angular blocky structure.

The upper (younger) till was deposited by the last (Late Wisconsinan) ice sheet. Upper till exposures generally reveal compact, gray to gray-brown, non-oxidized, stony till with a sand/silt matrix. This till is interpreted to be a lodgment **facies** and exhibits a weakly developed subhorizontal fissility. Where the upper till overlies the lower till, discrete pieces of the oxidized lower till occur as blocks within the matrix of the non-oxidized upper till. Locally, upper till is present as morainal deposits of **ablation till**. This material accumulated as a nonsorted mixture of sand, gravel, and silt with numerous large boulders directly at the ice front at sequential terminal positions during deglaciation. Ablation till is typically much less compact than lodgment till because the material was melted out of glacial ice at the margin during deglaciation rather than smeared beneath the great weight of the ice sheet as **lodgment till**. Morainal till deposits are present in the drainage basin in at least two areas—just south of the village of Usquepaug and on the northwest side of Purgatory Road at Fisherville. These moraines are extensions of the Old Saybrook and Hammonassett moraines in southeastern Connecticut.

Till underlies most upland areas in the Usquepaug-Queen Basin and extends beneath the stratified deposits in the valley. Although it is not a major aquifer because of small saturated thickness and low hydraulic conductivity, till is nevertheless an important unit in the glaciated northeast because it affects the circulation of ground water, particularly rates of recharge to and discharge from underlying bedrock aquifers.

Glacial stratified deposits (stratified drift) laid down by meltwater during retreat of the Late Wisconsinan ice sheet overlie till and bedrock in the Usquepaug-Queen River valley. These materials consist of gravel, sand, silt, and clay carried away from the ice front by meltwater streams, which commonly flowed directly or indirectly into glacial lakes. Glacial stratified deposits consist of mappable bodies of coarse-grained deposits (gravel, sand and gravel, and sand) and fine-grained deposits (very fine sand, silt, and clay). Coarse-grained, poorly sorted, and relatively angular gravels were deposited at and proximal to the ice front. This material commonly was laid down on top of ice at the glacier margin. Subsequent melting of the ice produced "collapsed" ice-contact **scarps** and **kettle holes** in and north of these proximal deposits. Finer grained and better sorted gravel and sand was deposited farther away from the ice margin commonly in deltas that prograded into glacial lakes. Well-sorted very fine sand, silt, and clay settled out as bottom sediments in the lakes. These "packages" of contemporaneously deposited stratified drift that grade from coarse grained near the ice margin to fine grained in areas distal from the ice are called morphosequences (Koteff and Pessl, 1981; Stone and others, 1992). Morphosequences are commonly 0.5 to 1 mi long and are present along the valley in shingled form; that is—the coarse-grained, collapsed, ice-contact northern part of one sequence is overlain by the fine-grained distal end of the next sequence to the north (see geologic section *A-A'* on pl. 1). This shingled relation between morphosequences occurs in at least four places along section *A-A'* and is the result of sequential deposition related to systematic northward retreat of the ice sheet during deglaciation.

The highest altitude to which stratified drift was deposited is controlled by the base altitude of the meltwater streams; this base altitude was most commonly either a large or small glacial lake. In the southern part of the Usquepaug River valley, a relatively large glacial lake existed in the Great Swamp Basin surrounding Wordon Pond, about 2 mi south of the study area. Glacial Lake Wordon controlled the level of meltwater deposition for the ice-marginal deltaic deposits in the Usquepaug River valley south of State Highway 138; the paleo-lake was impounded behind the Charlestown moraine to the south, and had a water-level altitude of about 100 ft above sea level that was controlled by a spillway across till and moraine southwest of the present Worden Pond. Smaller glacial lakes developed in the Queen River valley as the glacier margin retreated northward through the area. At the end of glacial retreat and meltwater deposition, these lakes were largely filled by the deltas and lake-bottom sediments that underlie the valley today (see map and geologic sections *A-A'*, *B-B'*, *C-C'*, and *D-D'* on pl. 1). The altitude of the paleo-water level in each lake is recorded by the unconformable **contact** between flat-lying, gravelly, fluvial topset beds and dipping, sandy, subaqueous foreset beds in the deltas. The topset-foreset contact beneath the flat, noncollapsed parts of delta surfaces commonly marks the boundary between gravel or sand and gravel beds and lower sand and silty sand beds (as shown in geologic sections *A-A'*, *C-C'*, and *D-D'* on pl. 1).

The coarse-grained stratified drift in the Usquepaug-Queen River valley consists predominantly of a series of ice-marginal deltaic morphosequences laid down sequentially northward in the lake. Fine-grained stratified drift consists of lake-bottom deposits laid down in deeper parts of the lake in front of the delta. In some places along the valley, successive deltas were built up against earlier ones, so that the surface gradient of the stratified drift is continuous from one deltaic morphosequence to the next. In other places, low areas underlain by lake-bottom sediments separate the deltaic sequences (geologic section *A-A'*, pl. 1).

Postglacial deposits consisting of floodplain alluvium and swamp deposits accumulated after deglaciation of the valley was complete and glacial lakes drained. Large blocks of detached glacial ice melted resulting in the formation of numerous kettle holes; at the same time, postglacial streams incised the glacial sediments and an integrated drainage system developed. Rivers and streams incised rapidly and modern floodplain surfaces developed early after lake drainage. Alluvium underlying the floodplain surfaces consists of relatively thin sand, gravel, and silt (reworked glacial deposits) with minor amounts of organic matter; thicker glacial deposits generally underlie the alluvium. As postglacial vegetation moved into the region, organic debris accumulated as peat and gyttja (freshwater organic-rich mud) in low-lying, poorly drained, closed basins created by melting of ice blocks. This peat and gyttja is as much as 30 ft thick in the large kettle-hole swamps.

The contour map of the bedrock surface (fig. 2) shows the altitude of the bedrock surface in the Usquepaug-Queen River Basin. Geologic sections, *A-A'*, *B-B'*, *C-C'*, and *D-D'* on plate 1 show the water table, lithology, and thickness of the stratified drift. Geologic section *A-A'*, drawn parallel to the axis of the Usquepaug-Queen River valley (pl. 1), shows the complex interbedding and lithologic **heterogeneity** of the stratified-drift aquifer.

Surface Water

The Queen and Usquepaug Rivers, their main tributaries and wetlands along them, are the principal areas of **ground-water discharge** from the stratified-drift aquifer. Continuous records of streamflow have been collected since 1975 at a USGS **continuous-record streamflow-gaging station** (01117420) on the Usquepaug River near Usquepaug (pl. 1). Average annual **runoff** from the basin ranged from 37.9 to 119 ft^3/s, and averaged 78.5 ft^3/s from 1975 through 1990. **Discharge** was measured monthly at nine partial-record stations from December 1988 through July 1991 (Kliever, 1995, table 7).

In Rhode Island, the minimum flow for which stream-water-quality standards have been developed is the 7Q10 flow, which is the minimum average daily flow for 7 consecutive days that can be expected to occur on the average once in 10 years (Rhode Island Statewide Planning Program and Rhode Island Department of Health, 1976, p. A-7). The 7Q10 flow at gaging station 01117420 at the basin outlet was 7.2 ft^3/s on the basis of Log-pearson type III statistics (Riggs, 1972).

Ground Water

The stratified-drift aquifer in the Usquepaug-Queen ground-water reservoir is unconfined. Locally, however, some parts of the aquifer may be semiconfined by fine-grained material beneath swamp deposits in wetland areas.

The configuration and altitude of the **water table** in the stratified-drift aquifer shown in figure 3 is based on water levels measured in 32 observation wells on September 13–14, 1989, when ground-water levels were near 1975–90 average annual conditions. The general direction of ground-water flow in the aquifer is from till and bedrock uplands toward the Queen and Usquepaug Rivers, and then down valley near the center of the river valley.

The altitude of the water table fluctuates several feet seasonally. During this study, four wells were equipped with digital recorders to provide continuous data on seasonal fluctuations of the water table in stratified deposits (three wells) and till (one well) from January 1989 through May 1991. Water-level data from the recorder wells and monthly water-level data from the 32 observation wells were published in a hydrologic data report by Kliever (1995). The range in fluctuations of the water table is affected by the rate of recharge to and discharge from the aquifer. Generally, ground-water levels in the Usquepaug-Queen River Basin decline from spring to autumn because most precipitation is returned to the atmosphere by **evaporation** and **transpiration** before it can recharge the water table. Additionally, ground-water levels decline during this period because water in the aquifer continues to move downgradient until it discharges to streams.

Stratified-Drift Aquifer

Thick and extensive deposits of saturated coarse-grained stratified drift form the major and most productive aquifer in the Usquepaug-Queen River Basin. This aquifer is capable of storing and transmitting large quantities of ground water through interconnected pore spaces. The unconsolidated materials map (pl. 1) shows the textural units based on grain-size distribution into which the stratified-drift materials were subdivided for this study. The stratified drift was subdivided into coarse-grained units (dominantly fine to very coarse sand and gravel) and fine-grained units (dominantly very fine sand, silt, and clay).

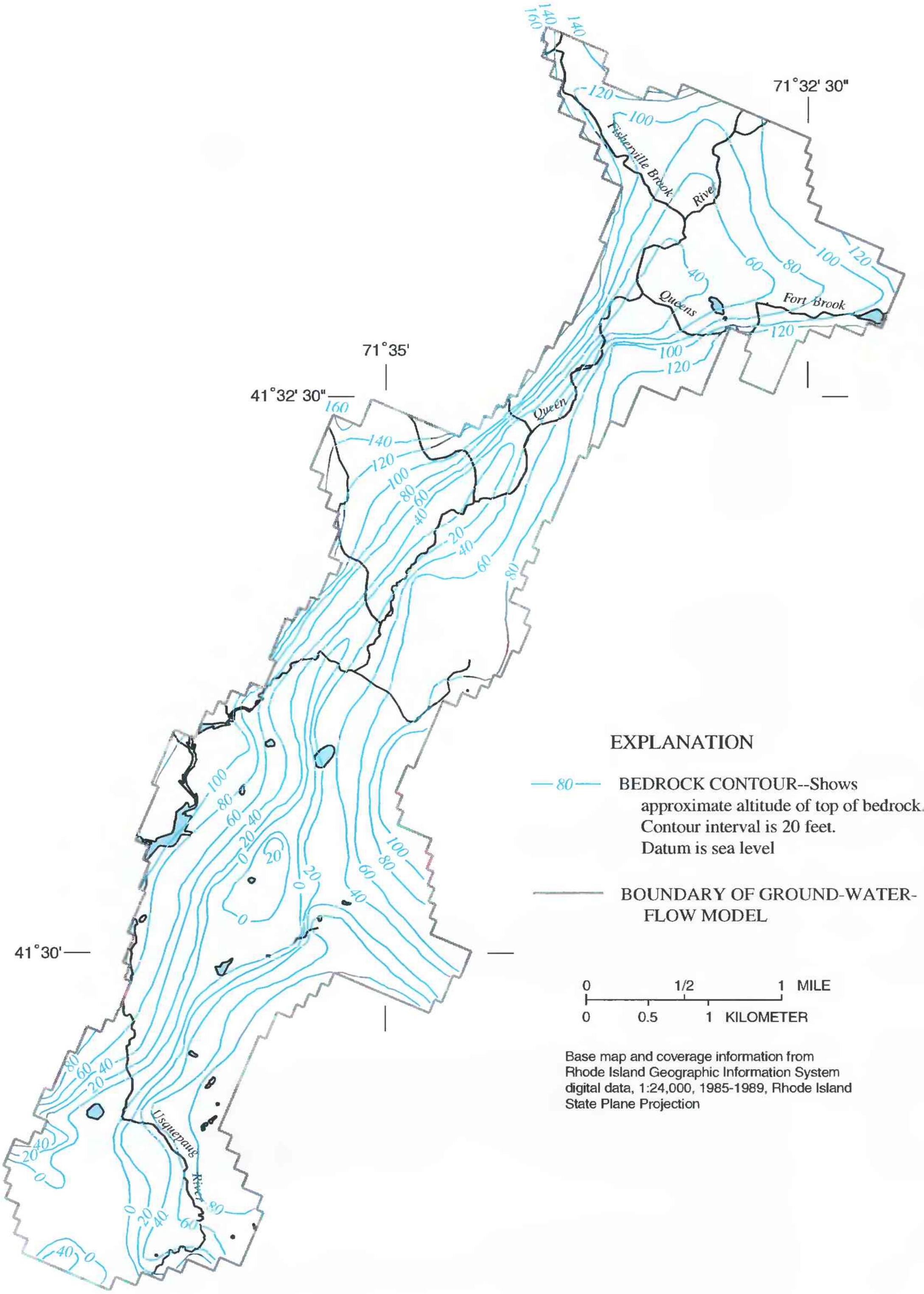


Figure 2. Bedrock surface in the Usquepaug-Queen model area, southern Rhode Island.

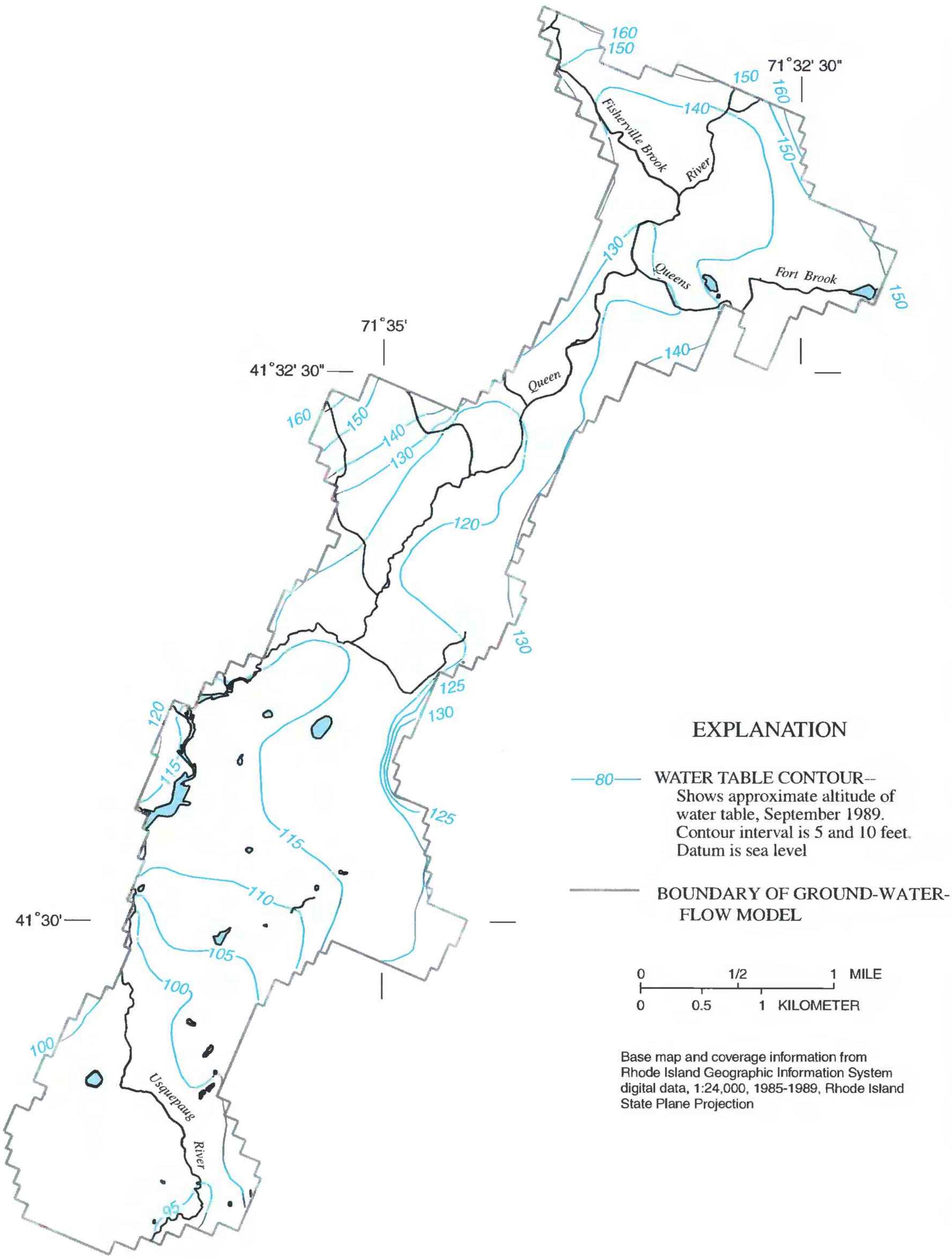


Figure 3. Configuration and altitude of the water table in the Usquepaug-Queen model area, southern Rhode Island, September 1989.

The stratified drift covers about 42 percent of the Usquepaug-Queen River Basin and reaches a maximum known thickness of 122 ft. The coarse-grained stratified-drift materials have the highest transmissivity and the capacity to yield relatively high volumes of water to wells. The fine-grained stratified-drift materials have the lowest transmissivity and consist predominantly of lake-bottom deposits. The stratified-drift aquifer is the only aquifer in the Usquepaug-Queen River Basin capable of producing yields of 0.5 Mgal/d or more from individual wells. This **unconfined (water table) aquifer** is in hydraulic connection with perennial streams, wetlands, and ponds. Yields of wells completed in the stratified-drift aquifer depend on natural recharge to the aquifer, the hydraulic properties of the aquifer, and the degree of stream-aquifer interaction.

Aquifer Characteristics and Hydraulic Properties

Stratified deposits are porous media that have a wide range of hydraulic conductivity dependent on their grain-size distribution (texture). Coarse-grained stratified deposits have the highest transmissivity and the capacity to yield relatively high volumes of ground water. In the Usquepaug-Queen study, aquifer characteristics and hydraulic properties were determined by evaluating data from wells and test holes drilled primarily in areas of stratified deposits thought to contain coarse-grained materials. These coarse-grained units are the most productive water-bearing materials in the stratified-drift aquifer. Some wells and test holes were drilled for the Usquepaug-Queen Basin study (data published in Kliever, 1995), and others were drilled as part of the data collection effort in the Upper Pawcatuck River Basin study (Allen and others, 1966). Hydraulic properties of the stratified-drift aquifer were determined using data from six aquifer tests conducted from 1946 to 1966 (Allen and others, 1966), and one aquifer test conducted by the RIWRB in 1970. Hydraulic properties also were estimated using detailed lithologic logs from 50 wells and test holes drilled from 1946 to 1989.

Discharge from pumped wells during aquifer tests ranged from 0.33 to 0.86 Mgal/d, with a **median** of 0.5 Mgal/d. The transmissivity of the stratified-drift aquifer determined from the aquifer tests ranges from 4,000 to 26,200 ft^2/d, with a median of 11,400 ft^2/d. The horizontal hydraulic conductivity determined from the aquifer tests ranges from 53 to 330 ft/d, with a median of 134 ft/d. For comparison, the transmissivity estimated from lithologic logs (for technique, see Dickerman, 1984) ranges from 1,900 to 27,800 ft^2/d, with a median of 7,100 ft^2/d, and the horizontal hydraulic conductivity ranges from 25 to 470 ft/d, with a median of 120 ft/d.

On the basis of an evaluation of the hydrologic data available from these 50 wells and test holes, 12 wells were selected to be simulated for ground-water development in the Usquepaug-Queen study using a ground-water-flow model. The hydraulic properties of the stratified-drift aquifer at these 12 wells suggests that the aquifer might be capable of supporting pumping of 0.5 Mgal/d or more to individual wells.

Sources of Recharge

Recharge was calculated using a computerized streamflow separation technique developed by Rutledge (1993). Total average annual recharge for the basin for 1975–90 was calculated using streamflow data from the gaging station on the Usquepaug River at State Highway 2 at the basin outlet to be 27.3 in., with an effective average annual **ground-water recharge** of 25.4 in. Effective average annual ground-water recharge (ground-water discharge) from 1975 to 1990 ranged from 12.5 in. in 1981 to 36.2 in. in 1983. Rutledge (1993) defines effective recharge as total recharge minus riparian evapotranspiration. Riparian evapotranspiration is the loss to the atmosphere of water from the stream channel and the saturated zone near the stream channel. Water potentially available for recharge in the Usquepaug-Queen River Basin is derived from three sources: (1) infiltration of precipitation that falls directly on the stratified drift, (2) lateral inflow from the till/bedrock uplands, and (3) leakage from streams.

Under natural conditions, the primary source of recharge to the aquifer is precipitation that falls directly on the stratified drift, where most of the rain and snowmelt infiltrates the ground and recharges the water table. Precipitation at the National Weather Bureau station in Kingston, R.I., averaged 51.2 in/yr from 1975 to 1990 of which 29.5 in. discharged to streams as runoff, and 21.7 in. was returned to the atmosphere by evaporation and transpiration. The 29.5 in. of average annual runoff is composed of 27.3 in. of total average annual recharge and 2.2 in. of average annual overland runoff.

The Usquepaug-Queen River valley is bordered by till/bedrock upland materials that have low hydraulic conductivity. These low-permeability materials restrict the amount of water that can move down through the soil to recharge the aquifer. Water that falls as precipitation on the uplands recharges the stratified-drift aquifer in three ways. Precipitation infiltrates the soil in the uplands and becomes ground water that flows downgradient through the till and bedrock toward the valley floor where it recharges the stratified drift. In areas not drained by upland streams, precipitation that does not infiltrate the soil flows overland and downslope until it reaches the valley floor where it infiltrates the stratified drift and becomes recharge. In areas drained by upland streams, precipitation becomes streamflow that is available for stream leakage in naturally losing stream reaches or for **induced recharge** under ground-water pumping conditions.

Under natural conditions, the water table usually slopes toward the stream and ground water discharges from the stratified-drift aquifer into the stream. Most streams in the basin receive **ground-water runoff** from the aquifer and are, therefore, **gaining streams**. Some stream reaches may lose water to the aquifer under natural conditions because the water level in the aquifer is below the stream level. Small tributary streams draining upland areas also may become naturally **losing streams** as they flow onto the more permeable valley-floor sediments.

When wells near the stream are pumped, the water-table gradient toward the stream decreases and ground-water runoff to gaining stream reaches is reduced. If pumping is of sufficient volume and duration, the **hydraulic gradient** may be reversed and water from the stream will move by **induced infiltration** through the streambed material into the stratified-drift aquifer.

The amount of water induced to flow from the stream into the aquifer and to a well is controlled by (1) the vertical hydraulic conductivity of the streambed material and the underlying aquifer, (2) the thickness of the streambed material, (3) the streambed area through which infiltration occurs, (4) the viscosity of the water in the stream, (5) the average difference in hydraulic **head** between the stream level and the aquifer water table within the streambed area where infiltration is occurring, and (6) the amount of water available in the stream.

The streambed materials of the Usquepaug and Queen Rivers primarily are composed of loosely packed sand and gravel, except in ponded and swampy areas. Vertical hydraulic conductivities in these loosely packed streambed materials are assumed to be higher than those of the underlying aquifer material, which typically is composed of layers of silt or silty sand. On the basis of this assumption, the effective streambed hydraulic conductivity was assumed to be the average vertical hydraulic conductivity of the underlying aquifer. Estimates of the vertical hydraulic conductivity of the underlying stratified-drift aquifer in the Usquepaug-Queen River Basin are based on aquifer tests conducted in similar materials in the adjacent Beaver River Basin, where the vertical hydraulic conductivity ranged from 0.40 to 18 ft/d. Hydraulic conductivity along most stream reaches was estimated using the median value in the Beaver River Basin to be 5 ft/d; except in ponded areas where it was estimated to be an order of magnitude lower (0.5 ft/d).

The quantity of water to be maintained in streams during low-flow periods limits the amount of water available for induced recharge to the underlying stratified-drift aquifer. For this study, all streamflow at or below the 7Q10 flow of 7.2 ft^3/s, at the Usquepaug River gaging station near Usquepaug R.I., was considered available for induced recharge to the aquifer. The 7Q10 flow is the minimum flow recommended by the R.I. Health Department to be maintained in streams in Rhode Island to meet stream-water-quality standards.

Bedrock and Till Aquifers

Bedrock is capable of providing usable amounts of water to wells and, therefore, constitutes an aquifer. In crystalline rocks, water moves principally along fractures. As a result, the yield of bedrock wells relates directly to the number of fractures the well intercepts. Water-bearing fractures in crystalline bedrock generally decrease in size and frequency with depth and become sparse at depths greater than 300 ft below sea level in Rhode Island (Allen and Kinnison, 1953, p. 27). Reported yields of wells with depths of 25 to 500 ft in the bedrock aquifers that underlie the Usquepaug-Queen River Basin range from 0.5 to 50 gal/min (Kliever, 1995, table 1). Data from Kliever (1995) show that the median yield of bedrock wells in the basin was 5 gal/min, and the median well depth was 200 ft.

Although till generally is not considered a reliable water-bearing material, it does constitute an aquifer capable of yielding small amounts of water for domestic and agricultural use. Generally, till does not yield more than 2 to 3 gal/min to large-diameter wells (Hahn, 1959). Wells in the till aquifer on the uplands commonly go dry during drought periods, and may go dry annually during late summer or early autumn.

Water Use

Withdrawals from ground-water and surface-water sources in the Usquepaug-Queen River basin averaged 0.28 Mgal/d during 1989 and 0.48 Mgal/d during 1990. Average monthly water pumping, return flow, precipitation, and runoff in the Usquepaug-Queen River Basin for 1989–90 are summarized in table 1. About 57 percent (0.16 Mgal/d) of the average pumping during 1989 was derived from ground-water sources and 43 percent (0.12 Mgal/d) was derived from surface-water sources. About 44 percent (0.21 Mgal/d) of the average pumping during 1990 was derived from ground-water sources and 56 percent (0.27 Mgal/d) was derived from surface-water sources. All water pumped was used and/or returned within the Usquepaug-Queen River Basin and water was not imported into the basin. There are no public water-supply systems in the Usquepaug-Queen River Basin. All pumpage in the basin was supplied from domestic wells, institutional wells, and irrigation sites that use either ground water or surface water.

The primary uses of water in the Usquepaug-Queen River Basin are for domestic, institution, and irrigation purposes. All domestic and institutional water is pumped from wells. Pumpage from domestic wells accounted for 56 percent (0.09 Mgal/d) of the average ground-water pumping during 1989 and 43 percent (0.09 Mgal/d) of the average ground-water pumping during 1990. Estimates of pumping for domestic use were based on the presence of 498 homes (shown on USGS topographic maps, photo revised 1970 and 1975) with 3 persons per household (U.S. Department of Commerce, 1991), multiplied by 60 (gal/d)/person (Solley, 1993). The pumping rate from wells for domestic use is assumed to be consistent throughout the year. Pumping from wells for institutional use averaged 0.07 Mgal/d during 1989 and 0.09 Mgal/d during 1990.

Irrigation, the largest single use of water in the Usquepaug-Queen River Basin, is pumped primarily from surface-water sources and accounts for 43 percent of the average pumping during 1989, and 62 percent of the average pumping during 1990. All pumping for irrigation during 1989 was from surface-water sources, whereas 90 percent of pumping for irrigation during 1990 was from surface-water sources and 10 percent was from ground-water sources. The average annual rate of pumping for irrigation from surface-water sources was 0.12 Mgal/d during 1989 and 0.3 Mgal/d during 1990. However, water was pumped for irrigation only during the growing season from June to September each year. Therefore, actual monthly rates of pumping are much higher than the average annual rates, and averaged 0.37 Mgal/d during the 1989 growing season and 0.90 Mgal/d during the 1990 growing season. Pumping rates for irrigation are highly dependent on precipitation. Pumping rates for irrigation ranged from a minimum of 0.36 Mgal/d during August 1989, to a maximum of 1.44 Mgal/d during June 1990. Precipitation during 1989 was evenly distributed throughout the growing season, and all water pumped for irrigation was used to maintain golf courses. During the 1990 growing season, precipitation was less evenly distributed, and water pumped for irrigation was used to maintain golf courses, turf farms, and small vegetable farms.

About 85 percent of the water pumped from domestic wells was returned to the ground through individual subsurface disposal systems, and therefore, was available to recharge the ground water in the basin. The amount of water lost to evapotranspiration through individual sewage-disposal systems was not determined, but is assumed to be small (probably less than 10 percent). Return flow from a single institutional wastewater-treatment facility to surface waters in the basin was about 57 percent (0.04 Mgal/d) of the average pumping for institutional use during 1989 and about 56 percent (0.05 Mgal/d) of the average pumping for institutional use during 1990. Irrigation water was not available for reuse in the basin because 100 percent of the water pumped for irrigation was assumed to be consumed through evaporation and evapotranspiration. Agricultural and golf course irrigation practices in the Usquepaug-Queen River Basin maximize irrigation efficiency, thereby minimizing return flow to the aquifer or overland runoff to surface-water bodies that could result from over-irrigating practices.

Table 1. Average monthly pumping, return flow, precipitation, and runoff in the Usequepaug-Queen River Basin, southern Rhode Island, 1989–90

[All data are given in million gallons per day. **Domestic (GW) Pumping:** Domestic pumping estimates are based on 498 homes with 3 persons per household and a coefficient of 60 gallons/person/day. **Institutional (GW) Pumping:** Metered data, except for January, February, and March 1990, which are estimated based on the December 1989 pumping rate and December 1990, which is estimated based on the November 1990 pumping rate. **Irrigation (GW and SW) Pumping:** Turf and vegetable farm irrigation estimates are based on acreage and a uniform application rate of 1 inch minus the weekly precipitation for the months of June, July, August, and September. Golf course irrigation estimates are based on an estimated pumping rate and the frequency of irrigation. **Domestic (GW) Return Flow**: Domestic return flow estimates are based on 85 percent of domestic pumping. **Institutional (SW) Return Flow:** Data collected from the Rhode Island Pollutant Discharge Elimination System (RIPDES) Permit Program data base, except for January, February, and March 1990, which are estimated based on the December 1989 return flow rate. **Precipitation:** Precipitation at Kingston, Rhode Island. **Runoff:** Runoff at Usquepaug River gaging station. GW, ground water; SW, surface water]

Month	Pumping								Return flow				Precipitation		Runoff	
	Domestic (GW)		Institutional (GW)		Irrigation (GW)		Irrigation (SW)		Domestic (GW		Institutional (SW)					
	1989	1990	1989	1990	1989	1990	1989	1990	1989	1990	1989	1990	1989	1990	1989	1990
January	0.09	0.09	0.08	0.09	0	0	0	0	0.08	0.08	0.04	0.05	37.3	124	33.9	69.2
February	.09	.09	.07	.09	0	0	0	0	.08	.08	.04	.05	73.1	73.8	36.6	90.5
March	.09	.09	.08	.09	0	0	0	0	.08	.08	.03	.05	98.5	40.1	47.3	58.1
April	.09	.09	.07	.09	0	0	0	0	.08	.08	.03	.05	134	124	87.9	80.8
May	.09	.09	.07	.09	0	0	0	0	.08	.08	.03	.04	122	129	99.5	84.0
June	.09	.09	.06	.09	0	.18	.37	1.26	.08	.08	.03	.04	106	21.8	59.7	38.9
July	.09	.09	.07	.08	0	.06	.37	.64	.08	.08	.04	.04	133	131	41.9	29.1
August	.09	.09	.06	.07	0	.06	.36	.65	.08	.08	.04	.04	116	46.4	35.9	18.5
September	.09	.09	.07	.10	0	.06	.38	.67	.08	.08	.04	.06	131	67.8	28.8	12.5
October	.09	.09	.07	.11	0	0	0	0	.08	.08	.04	.04	143	70.7	55.4	20.3
November	.09	.09	.08	.09	0	0	0	0	.08	.08	.04	.04	157	50.9	96.9	26.9
December	.09	.09	.09	.09	0	0	0	0	.08	.08	.05	.04	18.2	108	52.4	48.2
Average annual	.09	.09	.07	.09	0	.03	.12	.27	.08	.08	.04	.05	106	82.5	56.4	47.8

Of the total average amount of water pumped for all sources from the basin, 43 percent (0.12 Mgal/d) during 1989 and 27 percent (0.13 Mgal/d) during 1990 were available for reuse in the Usquepaug-Queen River Basin as return flow. Of the remaining total average amount of water pumped for all sources, 57 percent (0.16 Mgal/d) during 1989 and 73 percent (0.35 Mgal/d) during 1990 was lost to the system through consumption and evapotranspiration.

Basin Water Budget

Annual precipitation at the National Oceanic and Atmospheric Administration station at Kingston, R.I. (3 mi east of the Usquepaug-Queen River Basin), ranged from 38.2 in. (1980) to 70.2 in. (1983) and averaged 51.2 in. from 1975 through 1990. Total runoff from the streamflow-gaging station on the Usquepaug River near Usquepaug during that same period ranged from 14.3 in. (1981) to 44.8 in. (1983) and averaged 29.5 in. **Underflow (ground-water outflow)** from the basin was estimated from transmissivity, water-table gradient (fig. 3), and valley width at the gaging station and was considered negligible (0.01 Mgal/d).

Water pumped from ground-water and surface-water bodies from 1975 to 1990 was estimated to be about 0.4 Mgal/d. This estimate was calculated using ratios of average precipitation and runoff for 1975–90, and average precipitation, runoff, and water pumped during 1989–90 (table 2). Evaporation and transpiration (37 Mgal/d) were computed as the difference between total precipitation at Kingston, R.I. (88 Mgal/d), and the average annual total runoff for 1975–90 of the Usquepaug River gaging station (51 Mgal/d), plus estimated pumping (less than 1 Mgal/d) from ground water and surface water (table 2).

Water enters the Usquepaug-Queen River Basin as precipitation and leaves as surface outflow at the Usquepaug gaging station, underflow, pumpage, and evaporation and transpiration. A basin water budget quantitatively expresses the balance of water in the Usquepaug-Queen River Basin, and can be expressed as inflow equals outflow, plus or minus changes in storage. The net change in storage tends to be small over many years and can be considered negligible. The Usquepaug-Queen water-budget equation is expressed as follows:

$$\mathrm{INFLOW} = \mathrm{OUTFLOW}$$

$$P = Rt_{out} + W + ET$$

$$88 = 51 + <1 + 37, \qquad (1)$$

where:

P is precipitation, in Mgal/d;

Rt_{out} total runoff out of the basin, in Mgal/d;

W is water pumped from ground water and surface water, in Mgal/d; and

ET is evaporation and transpiration, in Mgal/d.

Table 2. Average water budget for the Usquepaug-Queen River Basin, southern Rhode Island, 1975–90

[Mgal/d, million gallons per day; (Mgal/d)/mi^2, million gallons per day per square mile; in., inch; <, actual value is less than value shown]

Budget item	Amount (Mgal/d)
Inflow	
Precipitation[1]	88
Total	88
Outflow	
Runoff from the Usquepaug River area upstream from the Usquepaug gaging station (36.1 mi^2)[2]	51
Underflow	([3])
Water pumped from ground water and surface water[4]	<1
Evaporation and transpiration[5]	37
Total	88

[1] Based on average precipitation (51.2 in,) at Kingston, R.I., 1975–90.

[2] Based on average runoff [1.41 (Mgal/d)/mi^2] of the Usquepaug River at Usquepaug, R.I., 1975–90.

[3] Underflow from the basin at the USGS streamflow-gaging station, estimated to be 0.01 Mgal/d, is considered negligible.

[4] Water pumped from ground water and surface water, estimated to be 0.4 Mgal/d, was calculated using ratios of average precipitation and runoff for 1975–90, and average precipitation, runoff, and water pumped during 1989–90.

[5] Difference between average precipitation at Kingston, R.I., and average runoff of the Usquepaug River at Usquepaug, R.I., 1975–90.

WATER QUALITY

Ground water, and surface water derived primarily from ground-water runoff in the Usquepaug-Queen River Basin, are suitable for most purposes on the basis of the analyses of physical properties and chemical constituents. However, the Usquepaug-Queen ground-water reservoir was categorized as "threatened" by the Rhode Island Department of Environmental Management (RIDEM) in its 1990 report to Congress on the state of the State's waters. As defined by

RIDEM, the "threatened" category is applicable to areas where ground water is presumed suitable for drinking water use, except for localized degradation. Nonpoint sources of pollution prevalent in these areas could adversely affect ground-water quality. Eighty percent of Rhode Island's ground water with respect to nonpoint pollution falls into the "threatened" category (Rhode Island Department of Environmental Management, 1990a).

Physical properties and chemical constituents were selected for analysis (table 3) on the basis of current land-use practices in the basin and are those considered most likely to have the greatest potential to affect drinking-water supplies in the basin. Water-quality data on individual wells and streams are available in a hydrologic data report on the Usquepaug-Queen River Basin (Kliever, 1995).

Study Methods

The present quality of ground water and surface water in the Usquepaug-Queen River Basin was determined by sampling 34 wells and 17 surface-water sites during August 4–17, 1993. Locations for all sampling sites are shown in figure 4. Wells and streams were sampled for **specific conductance, pH,** water temperature, dissolved oxygen, bicarbonate, carbonate, alkalinity, dissolved chloride, dissolved iron, dissolved manganese, dissolved sodium, and dissolved nitrite plus nitrate as nitrogen. Five duplicate ground-water samples and three duplicate surface-water samples were collected for quality-assurance analysis. In addition, specific conductance was measured at 40 surface-water sites during the summer 1992 and spring 1993, at a time when streamflow consisted primarily of ground-water runoff.

Table 3. Physical properties and chemical constituents of ground water and surface water in the Usquepaug-Queen River Basin, southern Rhode Island, August 4–17, 1993

[**Property or constituent:** Concentrations are in milligrams per liter unless otherwise noted. **Maximum contaminant level for drinking water:** Maximum contaminant level for inorganic chemicals established for public water-supply systems by the U.S. Environmental Protection Agency and adopted by the Rhode Island Department of Health (1991). Data from Kliever (1995). Ground-water samples were collected from August 9 through 17, and surface-water samples were collected from August 4 through 6, 1993. µS/cm, microsiemen per centimeter at 25 degrees Celsius; <, actual value is less than value shown; --, no data]

Property or constituent	Maximum contaminant level for drinking water	Ground water (39 samples)			Surface water (20 samples)		
		Minimum	Median	Maximum	Minimum	Median	Maximum
Specific conductance (µS/cm	--	44	92	495	37.0	68.5	122
pH (units)	[1]6.5-8.5	3.9	5.1	6.5	4.9	5.4	6.0
Temperature, water (°C)	--	8.5	11.2	17.4	15.0	21.0	25.5
Oxygen, dissolved	--	1.8	8.5	10.5	5.6	8.0	9.9
Bicarbonate (as HCO_3)	--	0	8.0	32	2.0	7.0	9.0
Carbonate (as CO_3)	--	0	0	0	0	0	0
Alkalinity (as $CaCO_3$)	--	0	7.0	26	2.0	6.0	8.0
Chloride, dissolved	[1]250	3.8	8.9	73	4.7	9.8	15
Iron, dissolved[2]	[1].3	.006	<.010	.28	.11	.22	.79
Manganese, dissolved[3]	[1].05	<.001	.014	1.2	.004	.017	.16
Sodium, dissolved	--	3.1	7.1	51	4.0	6.8	15
Nitrogen, nitrite plus nitrate, dissolved (as N)	10	<.05	.93	21	<.05	.23	.97

[1]Secondary maximum contaminant level established for public water-supply systems by the U.S. Environmental Protection Agency and adopted by the Rhode Island Department of Health (1991).

[2]36 samples.

[3]38 samples.

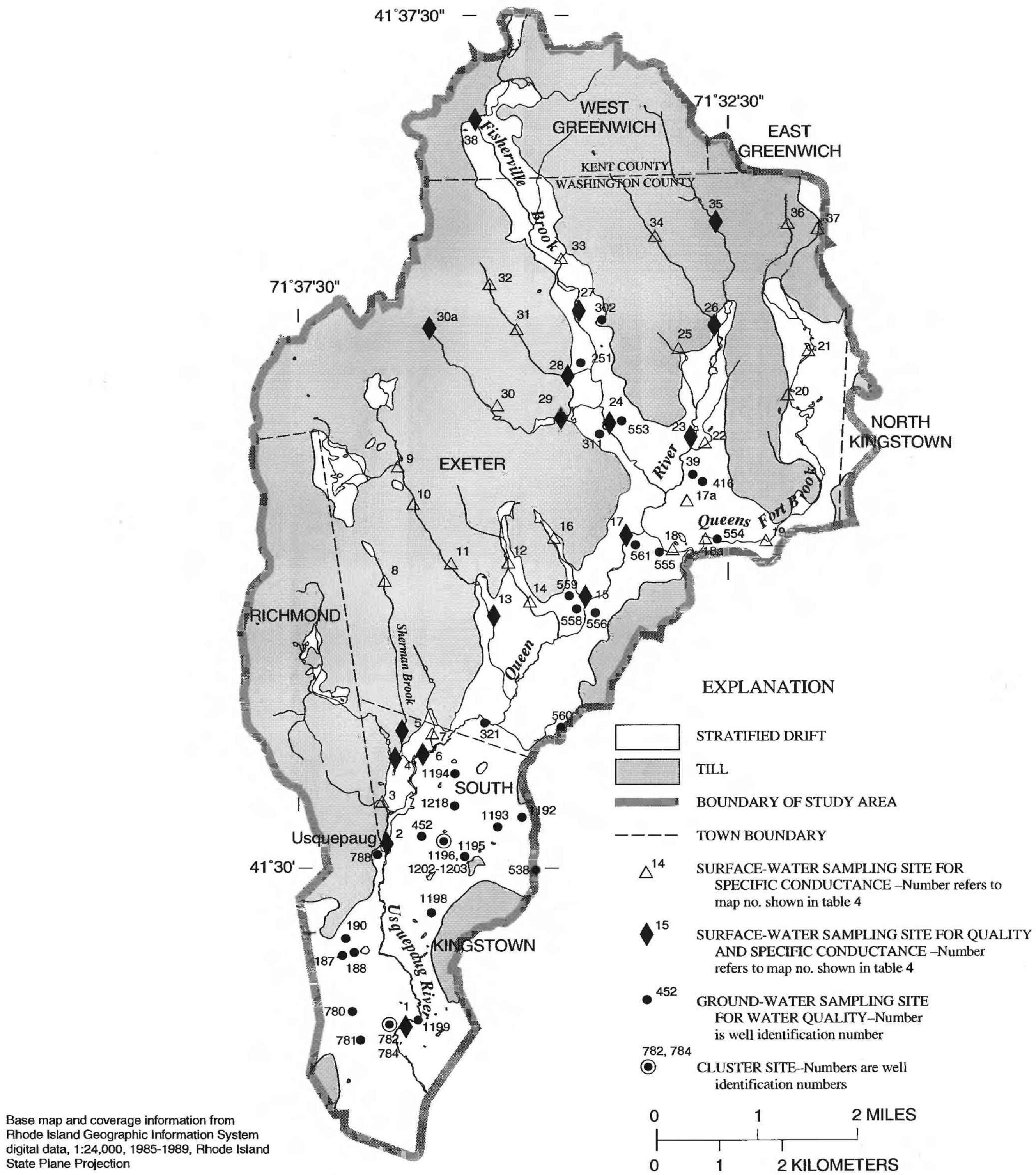


Figure 4. Location of ground-water and surface-water quality sampling sites in the Usquepaug-Queen River Basin, southern Rhode Island.

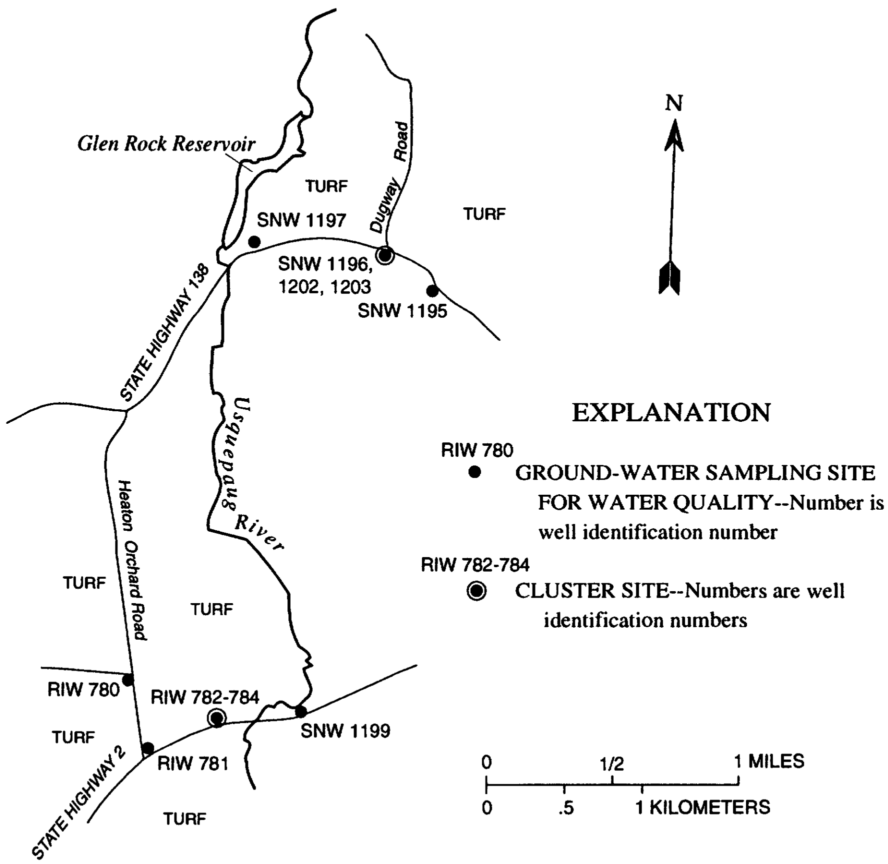


Figure 5. Ground-water-quality sampling sites on road right-of-ways at seven selected sites downgradient from commercially cultivated fields in the Usquepaug-Queen River Basin, southern Rhode Island.

For the purpose of clarity in this report, dissolved constituents are for filtered samples and total constituents are for unfiltered samples. In addition, dissolved or total nitrite (NO_2) plus nitrate (NO_3) will be referred to as dissolved or total nitrogen.

Eleven monitoring wells (fig. 5) were installed downgradient from highways and commercially cultivated fields along road right-of-ways at seven sites for this study to identify potential sources of ground-water contamination. These wells were used to monitor changes in ground-water quality caused by application of fertilizer and pesticide to cultivated fields, and de-icing salt to road surfaces along State Highway 2, State Highway 138, and Heaton Orchard Road. Nested wells were installed along State Highways 2 and 138. Nine of these 11 monitoring wells were included as part of the 34 wells sampled during August 4–17, 1993. Wells were screened at shallow, mid, and deep depths to obtain water-quality data throughout the full saturated thickness of the stratified-drift aquifer. Seven of the 11 monitoring wells were sampled monthly at shallow depths for 13 to 16 months for specific conductance, pH, water temperature, dissolved oxygen, dissolved chloride, and total nitrogen. Two additional monitoring wells, the mid- and deep-depth wells along State Highway 2 were sampled for 6 to 8 months. The last two wells, the mid- and deep-wells along State Highway 138, could not be sampled because silt and very fine sand partially clogged well screens severely limiting pumping.

All monitoring wells were screened in the upper part of the aquifer near the water table, except the mid- and deep-depth nested wells. Each monitoring well was constructed with 2-inch diameter polyvinyl-chloride (PVC) casing and finished with 3 ft of slotted PVC screen.

Surface Water

Surface water, derived primarily from ground-water runoff in the Usquepaug-Queen River Basin, is suitable for most purposes on the basis of the analysis of physical properties and chemical constituents. Water samples were collected from 17 surface-water sites (fig. 4) in August 1993, when streamflow was low and consisted primarily of ground-water runoff. Analyses of quality-assurance samples at 3 surface-water sites show consistent agreement with original samples. Median values of most physical properties and concentrations of chemical constituents in the surface-water samples, were similar to those in water samples from wells throughout the basin (table 3). The chemical and physical properties of surface water in the Usquepaug-Queen River Basin during August 4–6, 1993 are summarized in table 3.

Two basin-wide surveys of specific conductance were conducted at 40 surface-water sites (fig. 4), in summer (September 17, 1992) and spring (May 4, 1993), when streamflow consisted primarily of ground-water runoff. Specific conductance can be used to estimate the concentration of **dissolved solids** in water (Hem, 1985). Commonly, the concentration of dissolved solids is about 65 percent of specific conductance. Specific conductance from sewage effluent at the treatment plant outflow on September 17, 1992, and May 4, 1993, were not used in range or median determinations shown in table 3. Specific conductance ranged from 32 to 181 μS/cm, with a median of 59 μS/cm on September 17, 1992. Specific conductance ranged from 32 to 102 μS/cm with a median of 56 μS/cm on May 4, 1993. Estimates of median dissolved solids on the basis of these specific-conductance surveys range from 36 mg/L for the spring of 1993 to 38 mg/L for the summer of 1992.

The specific-conductance surveys indicate that stream water has low dissolved-solids concentration during periods of low flow. Specific conductance was highest in water from sewage effluent at the treatment plant outflow to Bear Swamp (table 4, site 17a). Specific conductance decreased from 300 μS/cm in the sewage effluent at the plant outflow to 69 μS/cm in the Queen River at the next downstream sampling site at Dawley Road. A summary of specific conductance and temperature at selected surface-water sites for September 17, 1992, and May 4, 1993, is shown in table 4.

Ground Water

Ground water in most parts of the Usquepaug-Queen River Basin is suitable for most purposes on the basis of the analyses of physical properties and chemical constituents. Water samples were collected during August 9–17, 1993, from 34 wells (fig. 4). Analyses of quality assurance samples show consistent agreement with original samples. The minimum, median, and maximum values for chemical constituents and physical properties of ground water sampled during August 9–17, 1993, are shown in table 3.

Specific conductance and concentrations of dissolved chloride and dissolved sodium were high in some parts of the Usquepaug-Queen ground-water reservoir. Nitrogen concentrations in some localized areas exceed the U.S. Environmental Protection Agency **maximum contaminant level** (MCL) for public drinking water (U.S. Environmental Protection Agency, 1994). Most pH levels for wells sampled in the basin were below (table 3) the USEPA secondary maximum contaminant level (SMCL) for public drinking water.

Specific Conductance

The specific conductance of water samples collected during August 9–17, 1993, in the Usquepaug-Queen River Basin from 21 wells away from roads ranged from 44 to 191 μS/cm, with a median of 75 μS/cm. For comparison, the specific conductance of samples from 13 wells near roads, also collected during August 9–17, 1993, ranged from 54 to 495 μS/cm, with a median of 232 μS/cm.

Specific conductance was measured for 13 to 16 consecutive months and ranged from 95 to 860 μS/cm (table 5) in nine monitoring wells installed on road right-of-ways at seven sites along major highways (fig. 5) where de-icing salts are applied to road surfaces. The minimum, median, and maximum specific conductance of water from these wells are shown in table 5.

Table 4. Summary of specific conductance and temperature at selected surface-water sites in the Usquepaug-Queen River Basin, southern Rhode Island, September 1992 and May 1993

[Site locations are shown in figure 4. No., number; µS/cm, microsiemen per centimeter at 25°C; °C, degrees Celsius]

Map No.	Selected surface-water sites: Location	September 17, 1992: Specific conductance (µS/cm)	September 17, 1992: Temperature (°C)	May 4, 1993: Specific conductance (µS/cm)	May 4, 1993: Temperature (°C)
1	Usquepaug River at State Highway 2	70	16.7	66	13.6
2	Usquepaug River at State Highway 138	58	18.0	57	13.8
3	Unnamed tributary to Glen Rock Reservoir at Glen Rock Road	43	15.8	42	11.2
4	Glen Rock Brook at Glen Rock Road	47	18.5	48	13.9
5	Sherman Brook at Glen Rock Road	43	17.0	40	11.4
6	Queen River at Dugway Road	66	16.0	62	12.4
7	Rake Factory Brook at Glen Rock Road	dry	dry	53	12.1
8	Sherman Brook at Hog House Hill Road	32	16.0	38	11.2
9	Locke Brook at Tripps Corner Road	42	16.0	63	12.5
10	Locke Brook at Sheffield Hill Road	50	15.7	62	12.2
11	Locke Brook at Hog House Hill Road	52	15.1	56	11.7
12	Unnamed tributary to Queen River at Hog House Hill Road	42	17.7	38	16.4
13	Locke Brook at Mail Road	51	15.7	59	11.8
14	Unnamed tributary to Queen River at Mail Road	44	16.8	49	14.2
15	Queen River at Liberty Road	68	15.8	62	12.5
16	Unnamed tributary to Queen River at Liberty Church Road	50	15.4	42	12.0
17	Queen River at Dawley Road	69	16.4	66	12.7
17a	Institutional sewage effluent at outflow to Bear Swamp	300	19.5	250	11.8
18	Queens Fort Brook near intersection of Dawley and School Lands Roads	147	15.2	102	13.2
18a	Queens Fort Brook at old unnamed road to Ladd	181	18.2	96	13.8
19	Queens Fort Brook at Slocumville Road	dry	dry	66	14.6
20	Queens Fort Brook at Pinoak Drive	63	20.6	58	15.1
21	Queens Fort Brook at State Highway 102	68	19.8	53	13.9
22	Unnamed tributary to Queen River at Reynolds Road	dry	dry	51	14.6
23	Queen River at Reynolds Road	64	18.6	56	15.0
24	Fisherville Brook at Liberty Church Road	63	17.5	56	13.6
25	Unnamed tributary to Queen River at Purgatory Road	98	17.4	85	13.6
26	Queen River at State Highway 102	38	19.4	32	15.2
27	Fisherville Brook at State Highway 102	49	19.5	46	13.9
28	Dutemple Brook at Hallville Road	78	16.6	72	12.7
29	Sodom Brook at Hallville Road	60	23.6	68	16.3
30	Sodom Brook at Sodom Trail	71	20.2	80	13.5
30a	Sodom Brook at State Highway 102	85	16.8	67	13.2
31	Dutemple Brook at State Highway 102	76	18.4	84	14.3
32	Dutemple Brook at Widow Sweets Road	68	20.1	84	13.9
33	Fisherville Brook at Pardon Joslin Road	38	16.5	42	13.8
34	Unnamed tributary to Queen River at Stony Lane	37	21.3	38	17.5
35	Queen River at Stony Lane	35	17.1	36	15.7
36	Reuben Brook at Stony Lane	dry	dry	38	14.6
37	Queens Fort Brook at Stony Lane	dry	dry	43	14.8
38	Fisherville Brook at Henry Brown Road	44	17.6	46	16.8

Table 5. Summary of specific conductance, dissolved chloride, and total nitrogen (nitrite plus nitrate) in water from monitoring wells along roadways in the Usquepaug-Queen River Basin, southern Rhode Island

[Data from Kliever (1995). **Well No.:** Locations of wells are shown in figure 5. Wells range in depth from 25.0 to 26.3 ft below land surface, except nested wells RIW 782, RIW 783, and RIW 784, which are 20.9 ft, 42.8 ft, and 88.7 ft deep. Ground-water samples collected monthly from March 1989 through June 1993. μS/cm, microsiemen per centimeter at 25 degrees Celsius; mg/L, milligram per liter; --, no data; <, actual value is less than value shown]

Well No.	Specific conductance (μS/cm)			Dissolved chloride (mg/L)			Total nitrogen, as nitrite plus nitrate (mg/L)		
	Minimum	Median	Maximum	Minimum	Median	Maximum	Minimum	Median	Maximum
RIW 780	124	130	138	7.7	10	14	2.0	2.7	5.0
RIW 781	189	247	583	8.0	18.5	150	4.7	13	20
RIW 782	460	529	544	12	31	33	5.3	24	29
RIW 783	473	484	494	31	32	34	3.0	13	14
RIW 784	533	547	556	35	36	40	22	24	24
SNW 1195	177	206	229	9.4	13	16	4.8	6.1	8.2
SNW 1196	95	116	172	11	14	17	1.3	2.6	4.0
SNW 1197	130	135	151	7.2	8.1	12	.3	1.5	3.5
SNW 1199	273	402	860	27	56	210	7.9	9.1	24

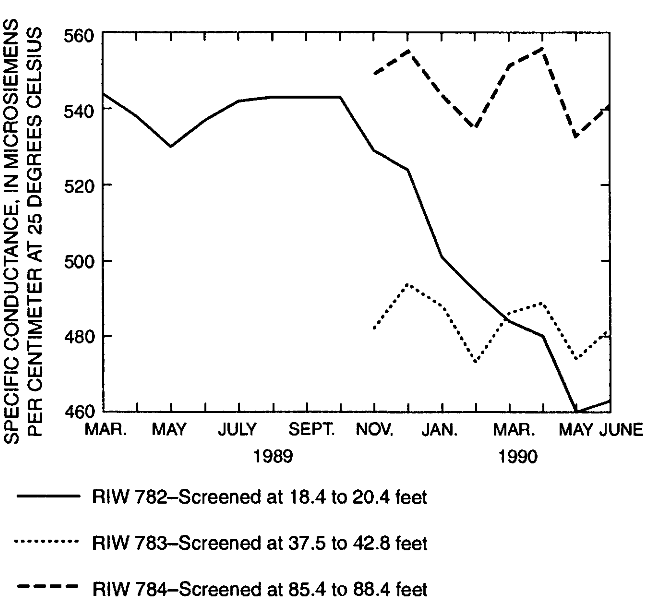


Figure 6. Monthly variations in specific conductance with depth in monitoring wells RIW 782-784 along State Highway 2 in the Usquepaug-Queen River Basin, southern Rhode Island, April 1989 to June 1990. (Data from Kliever, 1995).

The variation in specific conductance of ground water in the stratified-drift aquifer from depths of 18.4 to 88.4 ft below land surface, along State Highway 2, in Richmond wells (RIW) 782–784, during November 1989 through June 1990 are shown in figure 6. Variations in specific conductance also are shown in figure 6 for well RIW 782 from March 1989 through October 1990, prior to the installation of the middle and deep depth wells. Well RIW 782 (shallow) is screened 18.4 to 20.4 ft below land surface, well RIW 784 (middle) is screened 37.5 to 42.8 ft below land surface, and well RIW 783 (deep) is screened 85.4 to 88.4 ft below land surface. Specific conductances in nested wells along State Highway 2 at shallow, middle, and deep depths in the stratified-drift aquifer (fig. 6) are considerably higher than the basin median of 75 μS/cm. The high specific conductance (460 to 556 μS/cm) in these wells probably is due to the application of de-icing salts to road surfaces.

A comparison between specific conductance and dissolved chloride is shown for well SNW 1199 along State Highway 2 in South Kingstown in figure 7. A close correlation between specific conductance and dissolved chloride in water from this well is evident.

Dissolved Chloride and Sodium

The nine wells installed on road right-of-ways at seven sites also were used to monitor changes in ground-water quality caused by application of de-icing salt to road surfaces. Monthly ground-water samples from the monitoring wells along State Highway 2, State Highway 138, and Heaton Orchard Road in South Kingstown show elevated concentrations of dissolved chloride ranging from 7.2 to 210 mg/L (table 5).

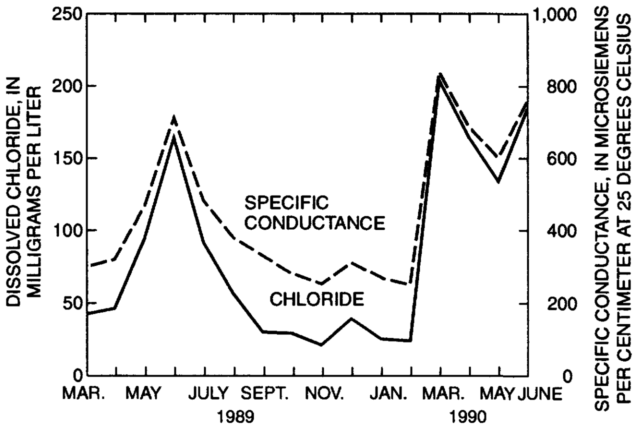


Figure 7. Monthly variations in chloride concentrations and specific conductance in well SNW 1199 along State Highway 2 in the Usquepaug-Queen River Basin, southern Rhode Island, March 1989 to June 1990. (Data from Kliever, 1995).

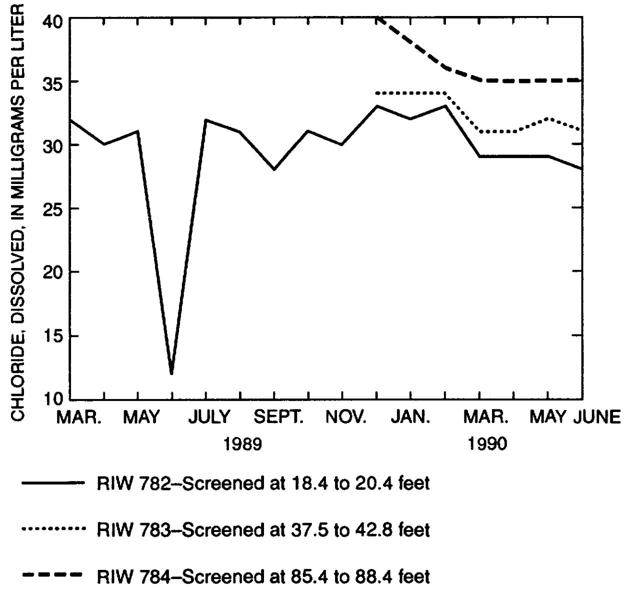


Figure 8. Monthly variations in chloride concentrations with depth in monitoring wells RIW 782-784 along State Highway 2 in the Usquepaug-Queen River Basin, southern Rhode Island, March 1989 to June 1990. (Data from Kliever, 1995).

Dissolved chloride concentrations shown in table 5 are considerably higher than those measured in the 39 ground-water samples collected from 34 wells throughout the Usquepaug-Queen River Basin during August 9–17, 1993 (table 3); those samples show dissolved chloride concentrations ranging from 3.8 to 73 mg/L, with a median of 8.9 mg/L. The high dissolved chloride concentrations in ground water in the nine monitoring wells (table 5) probably are due to application of de-icing salts to the nearby highways.

Dissolved sodium, although not sampled monthly, was sampled during August 9–17, 1993, in 34 wells, which included 7 of the 11 monitoring wells. Dissolved sodium in the 34 wells ranged from 3.1 to 51 mg/L with a median of 7.1 mg/L (table 3).

Variations in concentrations of dissolved chloride of ground water in the stratified-drift aquifer from depths of 18.4 to 88.4 ft below land surface, along State Highway 2, in Richmond wells (RIW) 782–784, for December 1989 through June 1990 are shown in figure 8. Variations in dissolved chloride also are shown in figure 8 for well RIW 782 from March 1989 through October 1990 prior to the installation of the middle and deep depth wells. Dissolved chloride in wells along State Highway 2, at shallow (12 to 33 mg/L), middle (35 to 40 mg/L), and deep (31 to 34 mg/L) depths in the stratified-drift aquifer (fig. 8), are considerably higher than the median of 8.9 mg/L for the basin. The high dissolved chloride in these wells probably is due to the application of de-icing salts to road surfaces.

A domestic well, Exeter well (EXW) 302, on the south side of State Highway 102 in the northern part of the Usquepaug-Queen River Basin also shows the effect of highway de-icing salts on ground-water quality. Water from EXW 302 has a specific conductance of 240 µS/cm, dissolved chloride of 61 mg/L, and dissolved sodium of 35 mg/L. In the central part of the basin, ground water from monitoring well EXW 556 near the bottom of a hill at the corner of Liberty Road and Kingston Road also shows the effect of highway de-icing salts; water from this well has a specific conductance of 137 µS/cm, a dissolved chloride of 28 mg/L, and a dissolved sodium of 20 mg/L.

Nitrogen

In Rhode Island, high nitrogen concentrations in ground water commonly are attributed to the land application of fertilizer. Of the three basic types of fertilizers—nitrogen, phosphate, and potash—applied to crops in Rhode Island, nitrogen fertilizers are the only type considered a serious threat to ground-water quality (Rhode Island Department of Environmental Management, 1990a). Septic-tank discharge also can cause high concentrations of nitrogen in ground water.

Concentrations of dissolved nitrogen were high in ground water in the Usquepaug-Queen River Basin as indicated by the median dissolved nitrogen as NO_2 plus NO_3 (referred to hereafter as dissolved nitrogen) of 1.06 mg/L for 34 filtered samples collected during August 9–17, 1993. Water samples for 30 of the 34 wells analyzed for dissolved nitrogen, however, were less than the USEPA MCL limit of 10 mg/L for public water-supply systems. The four wells with high concentrations of dissolved nitrogen that exceed the USEPA MCL were in the set of nine wells at seven sites downgradient from commercially cultivated fields. Dissolved nitrogen in these wells ranged from 10 to 21 mg/L during sampling in August 1993.

Total nitrogen as NO_2 plus NO_3 (referred to hereafter as total nitrogen) concentrations also were analyzed for in these nine monitoring wells where 115 unfiltered samples ranged from 0.3 to 29 mg/L (table 5). Concentrations of total nitrogen were high in water samples from all nine monitoring wells from March 1989 through June 1990 (Kliever, 1995). Samples from three shallow monitoring wells along State Highway 138 and one shallow monitoring well on Heaton Orchard Road did not exceed the USEPA MCL of 10 mg/L for total nitrogen. However, most samples and all median concentrations for total nitrogen from five monitoring wells along State Highway 2 did exceed the USEPA MCL for public water-supply systems on the basis of data collected by Kliever (1995).

Total nitrogen concentrations of water in wells RIW 782–784 exceed the USEPA MCL limit of 10 mg/L for drinking water at shallow, middle, and deep depths in the stratified-drift aquifer during most months from December 1989 to June 1990 (fig. 9). Data from Kliever (1995) show that 17 (89 percent) of 19 samples analyzed from December 1989 to June 1990 in nested wells along State Highway 2 exceeded the USEPA MCL limit of 10 mg/L. On the basis of data from Kliever (1995), water quality in shallow well RIW 782, the only well available for sampling from April 1989 to June 1990, exceeded the USEPA MCL for 24 (89 percent) of 27 samples. The high total nitrogen in wells RIW782–784 probably is due to the application of fertilizer to commercially cultivated turf fields.

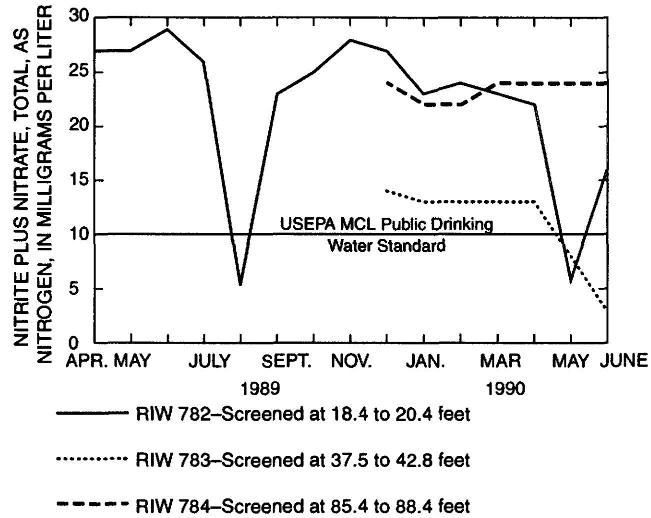


Figure 9. Monthly variations in nitrogen concentrations with depth in monitoring wells RIW 782-784 along State Highway 2 in the Usquepaug-Queen River Basin, southern Rhode Island, April 1989 to June 1990. (Data from Kliever, 1995).

Pesticides

Organic pesticides are being detected with increasing frequency in ground water in Rhode Island, with aldicarb being the most frequently detected pesticide (Rhode Island Department of Environmental Management, 1990a). Two shallow USGS monitoring wells, RIW 782 along State Highway 2 and SNW 1196 along State Highway 138, were sampled for analysis of pesticides in June 1989. Samples from each well were analyzed for 1-naphthol, 3-hydroxycarbofuran, aldicarb, aldicarb sulfone, aldicarb sulfoxide, carbaryl (sevin), carbofuran, total methomyl, oxamyl (vydate), and total propham. Pesticides were not detected in well SNW 1196. Three pesticides were detected in well RIW 782. Concentrations of pesticides detected in well RIW 782 were aldicarb sulfone, 1.5 µg/L (USEPA draft **lifetime health advisory,** 7 µg/L); carbofuran, 0.8 µg/L (USEPA MCL, 40 µg/L); and oxamyl (vydate), 2.8 μg/L (USEPA MCL, 200 μg/L). None of these concentrations exceed the MCL's for public water-supply systems.

Fifteen wells in the Usquepaug-Queen River Basin were sampled for pesticides by the RIDEM as part of the agency's statewide private-well survey in 1986 (Rhode Island Department of Environmental Management, 1990b). Wells were sampled for alachlor, aldicarb, butylate, carbaryl, carbofuran, chlorothalonil, 2,4-D, dachtal, diazinon, dicamba, dinoseb, endosulfan, eptam, mancozeb, metribuzin, oxamyl, and permethrin. Three of these pesticides—carbaryl, carbofuran, and dicamba—were detected in 5 wells. Concentrations of carbaryl in 4 wells ranged from 0.17 to 0.35 μg/L (USEPA lifetime health advisory, 700 μg/L); concentrations of carbofuran in one well was 2.0 μg/L (USEPA MCL, 40 μg/L); and concentrations of dicamba in 2 wells ranged from 0.29 to 1.41 μg/L (USEPA lifetime health advisory, 200 μg/L).

Other Properties

Ground water in the Usquepaug-Queen River Basin is somewhat corrosive, with a hydrogen-ion concentration, or pH, ranging from 3.9 to 6.5, with a median of 5.1. The pH value for 33 of 34 wells sampled during August 9–17, 1993, violate the secondary maximum contaminant level (SMCL) of 6.5 to 8.5, established for public water-supply systems by the USEPA and adopted by the RIDOH.

Dissolved manganese in ground water throughout the Usquepaug-Queen River Basin generally is present in concentrations less than the RIDOH SMCL of 0.05 mg/L. The median dissolved manganese concentration for 38 wells sampled during August 9–17, 1993, was 0.014 mg/L. However, some local areas have dissolved manganese concentrations that did exceed the SMCL in six wells (Kliever, 1995). Manganese in these wells ranged from less than 0.001 to 1.2 mg/L.

GROUND-WATER-FLOW MODEL

Before creating a numerical (quantitative) model of a ground-water system, it is necessary to first understand the natural system and create a conceptual (qualitative) model. The **conceptual model** must incorporate the important aspects of the natural system yet be simple enough to be used as a guide for creating the numerical model.

Conceptual Model

The part of the Usquepaug-Queen River Basin selected for simulation consists of a 7.5-mi^2 area of stratified drift; the model boundary is shown in figure 1. The natural system and corresponding conceptual model of the ground-water-flow system are shown in figure 10. The two most important aspects of the conceptual model are how the aquifer is recharged with water and how the aquifer discharges water.

In the conceptual model, the stratified-drift aquifer is recharged in two ways: direct precipitation and lateral recharge from the till/bedrock uplands. Direct precipitation is assumed to be distributed uniformly over the area underlain by the aquifer. Lateral recharge from the till/bedrock uplands occurs along the edge of the aquifer. The stratified-drift aquifer also may be recharged by infiltration from streams and wetlands if the ground-water level is below the stream or wetland water level. This may happen naturally, or ground-water levels may be drawn down artificially by ground-water withdrawals. The aquifer is underlain by a thin layer of till that is underlain by bedrock. It was assumed that no ground water flows either to or from the underlying bedrock. In reality, flow from the bedrock to the stratified-drift aquifer does occur. However, this leakage to or from the underlying bedrock was considered to be negligible, and bedrock was not included in the ground-water-flow model.

Discharges from the aquifer also occur in three ways: evapotranspiration, pumping from wells, and discharge to streams and wetlands. Evaporation and transpiration is the movement of water from the ground into the atmosphere by a combination of direct evaporation and transpiration, whereby water is used by plants and released to the atmosphere. The current pumping rate of 0.4 Mgal/d (table 2) from wells was considered negligible. For simulations of future ground-water development, it was assumed that highly efficient wells would be installed and that all water withdrawn from wells would be exported from the basin for use elsewhere. During average conditions, much of the water in the aquifer discharges to the streams and wetlands.

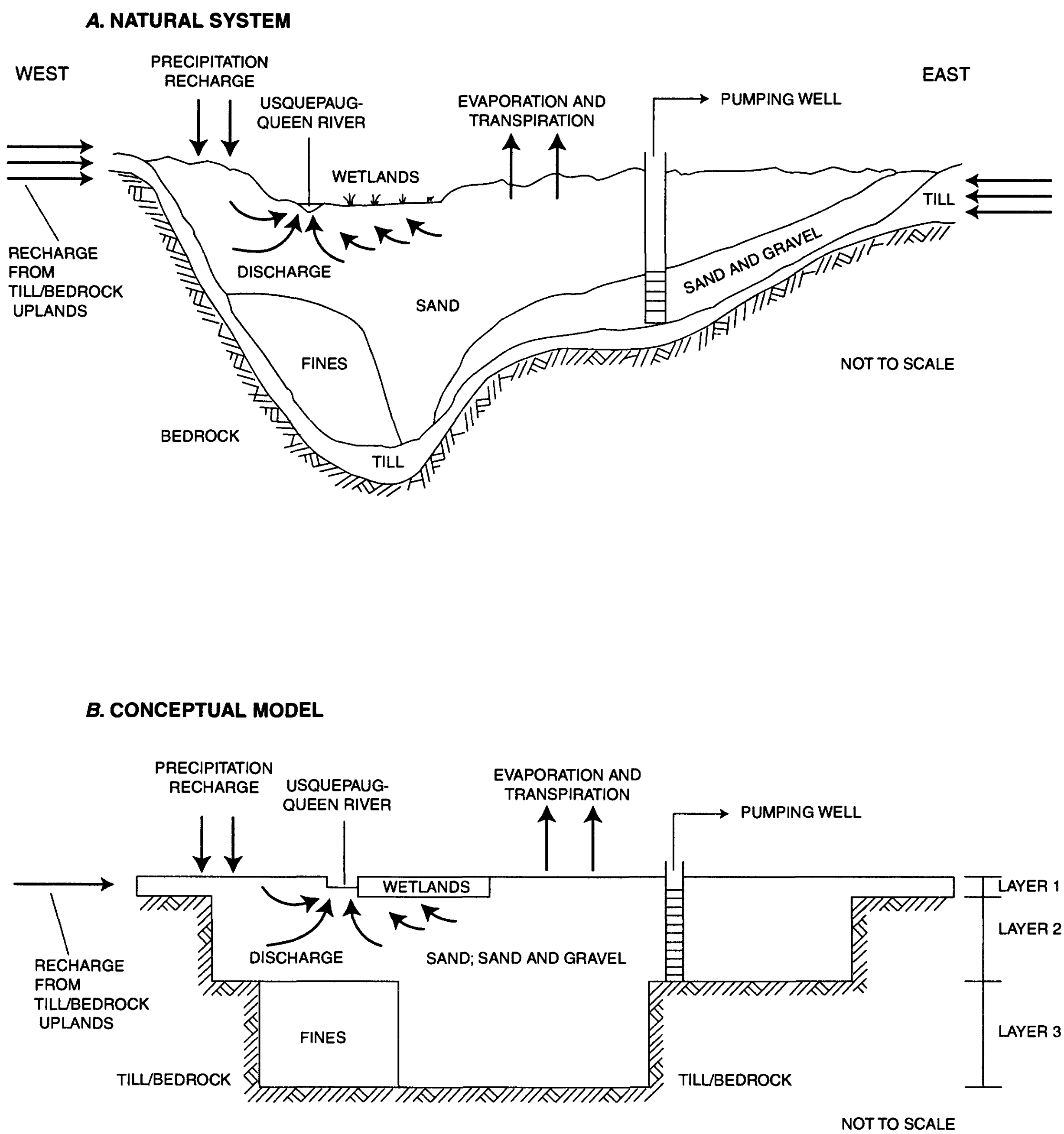


Figure 10. Natural system and conceptual model of ground-water flow in the Usquepaug-Queen River Basin, southern Rhode Island.

Although this model does not fully characterize the actual conditions in the stream-wetland-aquifer system, any deviations probably do not introduce large errors in conceptualization of the system or in numerical simulations based on this conceptual model.

Numerical Model

Numerical models of ground-water flow are widely used in the analysis and management of water resources. A numerical model constitutes a series of equations that mathematically represent a natural system such as an aquifer. These numerical models are complex and, therefore, are coded into computer programs. Generic models of aquifers have been developed that can be customized and calibrated to represent an individual natural system.

A finite-difference model (MODFLOWP) developed by Hill (1992) was used in this study. This model adds automated parameter estimation to the widely used MODFLOW model developed by McDonald and Harbaugh (1988). The model is based on a block-centered, finite-difference method to approximate the differential equations that describe the flow of ground water. Solution of these equations requires subdivision of the model area into a grid of rectangular blocks called cells; in this study, each cell was 400 ft in the longitudinal direction and 200 ft in the lateral direction, in order to define the long, narrow northeast-southwest trending Usquepaug-Queen valley aquifer. The model grid (fig. 11) consists of 91 rows and 68 columns. Based on the surficial geologic materials map and cross sections (pl. 1), the model was divided into three layers (fig. 10) to allow the simulation of wetlands, represented in layer one; course-grained stratified deposits, represented in layers one, two, and three; and fine-grained sediment (primarily glacial lake-bottom material) represented in layers 2 and 3. Only those cells representing the aquifer (including the fine-grained sediment) or the wetlands are considered 'active' and are involved in the computations.

A finite-difference equation that approximates flow in the block is evaluated at each model grid cell, and the set of equations for the entire system is solved simultaneously. The solving technique used in the Usquepaug-Queen model is the **preconditioned conjugate-gradient 2 (PCG2)** method developed by Hill (1990).

Boundary Conditions

After creating the grid for the model, the next step is to define boundary conditions to match the conceptual model. The bottom of the model was set as a **zero-flux or no-flow boundary**. Where the edge of the model coincides with a ground-water drainage divide, the model boundary was defined as a zero-flux boundary. If ground water is pumped from wells near a drainage divide, the divide may move outward to allow more water to be captured by the enlarged basin area. No pumping wells are simulated in the Usquepaug-Queen ground-water-flow model near ground-water drainage divides determined from flowlines. The model was designed to be conservative by keeping the ground-water divide stationary. The remainder of the edge of the model was defined as a **specified flux** boundary by using the well package in MODFLOWP. The specified flux boundary was used to simulate long-term average annual recharge from ground-water inflow from the till/bedrock uplands to the active model area. The ground-water inflow was calculated based on 27 in/yr of recharge to the till/bedrock uplands. The top of the model was simulated as a variable-flux boundary using the MODFLOWP evapotranspiration and recharge packages. Recharge from precipitation was applied at a rate of 27 in/yr, and evaporation and transpiration was applied at a maximum of 23.7 in/yr when the water table is at land surface and decreases to zero when the water table is 4 ft or more below land surface. The interface between the stream and the aquifer was modeled using a stream-routing package developed by Prudic (1989). Where streams flow into the model area, model flows were set using flows measured at partial-record sites established for this study.

Steady-State Calibration Using Parameter Estimation

Normally, one or more properties of a ground-water-flow system are not well known and models are calibrated to match observations of flow and head in the real system. In the Usquepaug-Queen ground-water-flow model, the properties of saturated thickness, boundary conditions, and recharge rates were relatively well known. However, the property of aquifer hydraulic conductivity was not as well known.

For this study, parameter estimation by means of nonlinear regression was used to calibrate the model instead of the more common trial-and-error method. Although methods for automated parameter estimation have existed for some time, it is only recently that these methods have been adapted for use with MODFLOW.

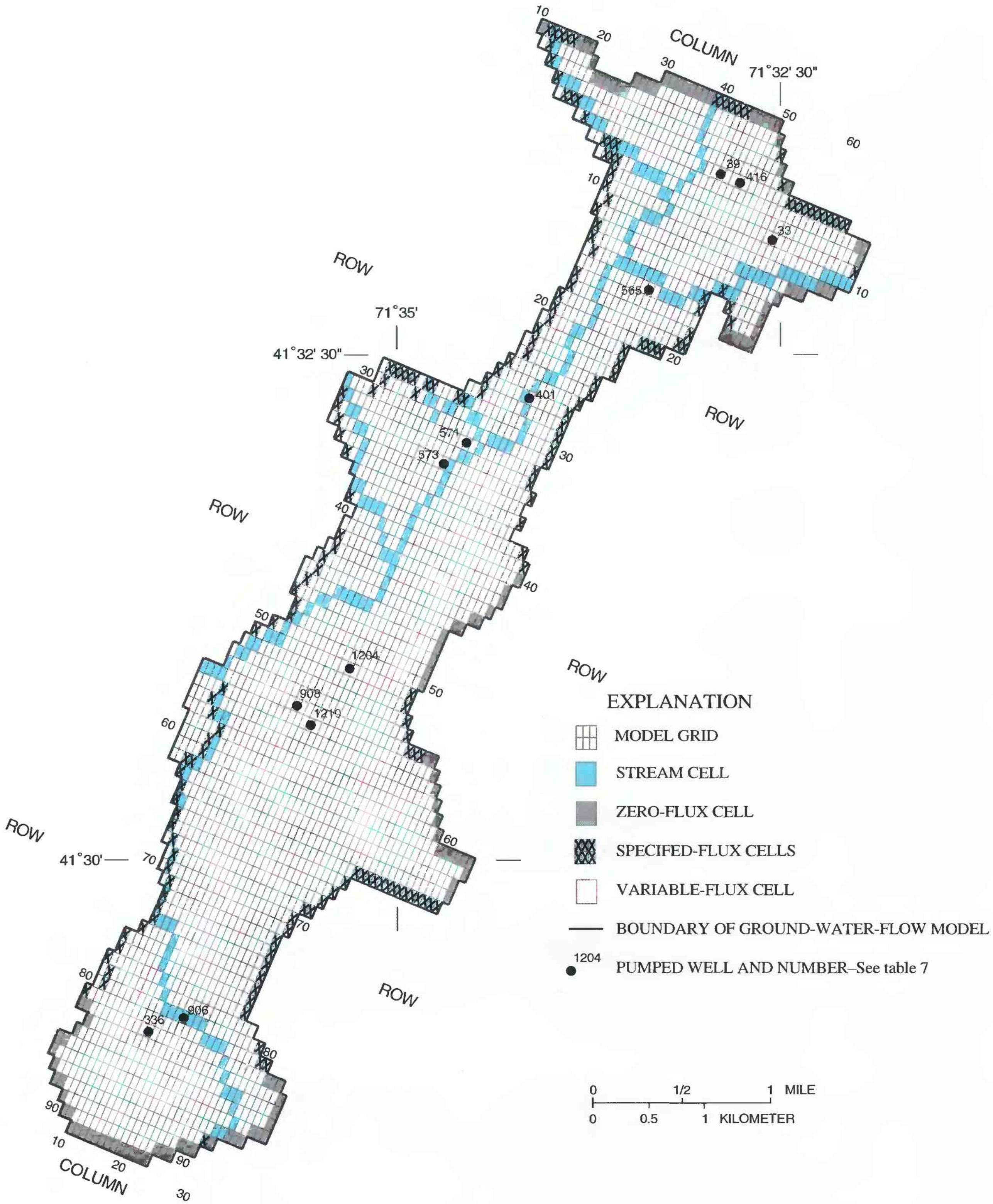


Figure 11. Finite-difference grid, cell boundary conditions, and location of pumped wells for the Usquepaug-Queen model area, southern Rhode Island.

Calibration Procedure

Parameter values representing hydraulic properties of the aquifer were adjusted during model calibration to produce a model that could approximate 24 measurements of hydraulic head (fig. 12), and 2 measurements of streamflow gains, one in the upper part and one in the lower part of the Usquepaug-Queen ground-water-flow model (fig. 12). Head and flow measurements from September 1989 were used to calibrate the model. September 1989 was chosen because measured heads in the stratified-drift aquifer were near long-term-average conditions. Measured streamflows in September 1989 were less than long-term-average conditions.

Model parameters were estimated using a nonlinear-regression method developed by Cooley and Naff (1990) and modified for application with MODFLOW by Hill (1992). The method finds parameter values that minimize the sum of squared errors (*SSE*) for a model based on a set of assumptions about the aquifer system, where *SSE* is defined as:

$$SSE = \sum [w_i^{1/2} e_i]^2, i = 1, n \qquad (2)$$

where

e_i is the difference between the simulated and measured values of head and streamflow gains/losses at measurement point *i*;

$w_i^{1/2}$ is the square root of the weight assigned to the error in the measured value of measurement *i*;

$w_i^{1/2}e_i$ is the weighted residual corresponding to measurement *i*; and

n is the number of observations.

The regression procedure ensures that optimal parameter values are obtained for a given set of assumptions about the aquifer system. The remaining error can be ascribed to the use of incorrect assumptions concerning the model design. The nonlinear regression also provides estimates of the reliability of estimated parameter values and the correlation between model parameters. This information is used to improve the calibration through (1) identification of parameters to which the model is insensitive, and (2) grouping of correlated parameters.

Estimates of Aquifer Properties

Six parameters were defined to represent various properties of the aquifer. Four of these parameters were horizontal hydraulic conductivity for different zones in the aquifer. The fifth parameter was the ratio of vertical to horizontal hydraulic conductivity (**anisotropy**) in the aquifer, and the last parameter was the hydraulic conductivity of the streambed material. Using MODFLOWP, it was determined that the model is insensitive to four of these parameters, including two of the horizontal hydraulic conductivities, anisotropy, and hydraulic conductivity of the streambed. These four parameters were set to reasonable values (as explained below) and were not estimated by nonlinear regression. The model may have been insensitive to these parameters because the hydrology of the aquifer is controlled by other factors. The stratified-drift aquifer is long and narrow with a stream running down the center of the valley. Stream stage tends to control ground-water levels in the stratified-drift aquifer near the stream, as well as water levels in the wetlands. Because of these constraints, the hydraulic properties of the aquifer itself may not be as important in determining heads as they are in wider valley aquifers. Additionally, head measurements for this study were primarily made in the coarser material near the water table, and therefore, may not be affected by the hydraulic properties of the finer material or material at depth.

Because in many cases the flow in an aquifer is predominantly horizontal, horizontal hydraulic conductivity commonly controls ground-water flow. The horizontal hydraulic conductivity is expected to vary by two orders of magnitude within this aquifer, so the aquifer was divided into four zones on the basis of lithologic logs (Kliever, 1995) and the surficial geologic materials map (pl. 1). Most of the aquifer is composed of glacial meltwater sediments. These materials were divided into three categories: sand and gravel, sand, and fine-grained sediment (very fine sand, silt, and clay). Using MODFLOWP, hydraulic conductivity of the sand and gravel and sand units was determined to be highly correlated and could not be estimated reliably independently. Therefore, sand and gravel and sand were combined into one zone for coarse-grained stratified deposits. The resulting estimated hydraulic conductivity for this zone was 101 ft/d (figs. 13*A*, 13*B*, and 13*C*).

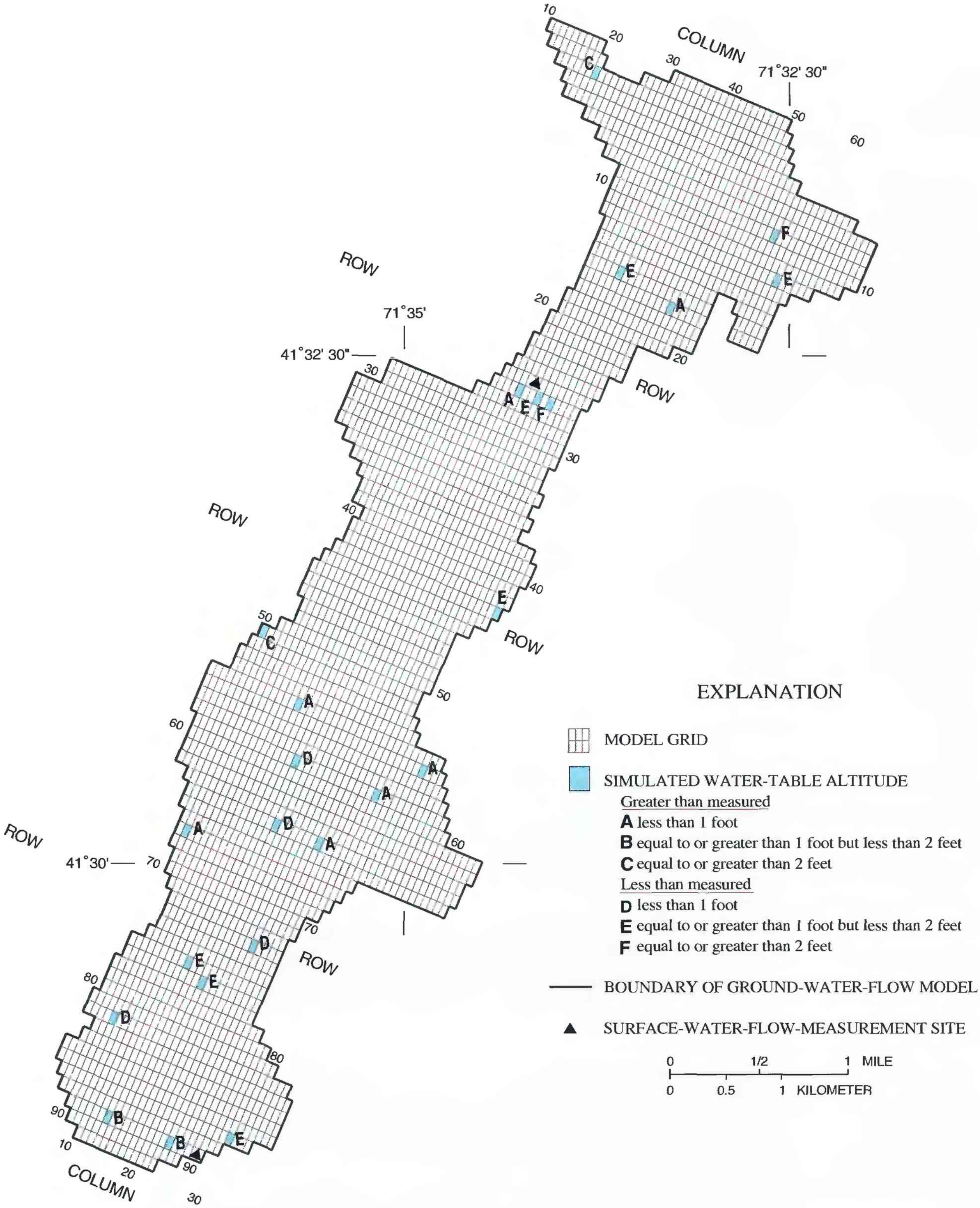


Figure 12. Spatial distribution of differences between simulated and measured water levels for the calibrated steady-state model for the Usquepaug-Queen model area, southern Rhode Island.

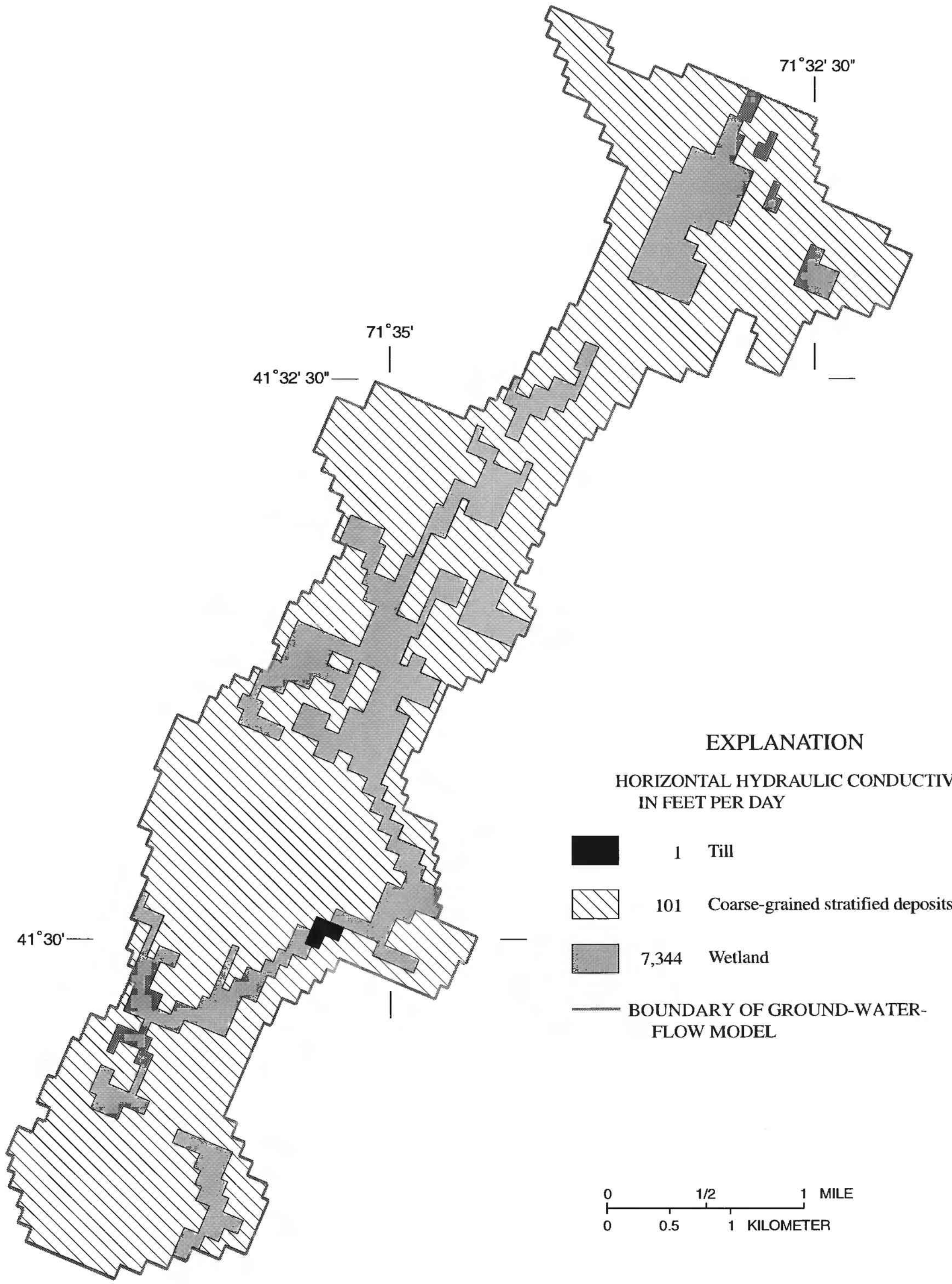
This value is typical for medium sand and reasonable on the basis of results from aquifer tests conducted in similar materials in southern Rhode Island (Dickerman, 1984; Dickerman and Bell, 1993). The model was insensitive to the hydraulic conductivity of the fine-grained sediments, perhaps because the sediments are at the bottom of the aquifer and of limited areal extent, and because few hydraulic head data were available in that zone. Therefore, the hydraulic conductivity of the fine-grained sediment zone was not estimated by parameter estimation but set at a value of 55 ft/d (figs. 13*B* and 13*C*), which is typical for a fine sand (Dickerman, 1984, table 2). Wetlands were simulated as a zone in layer 1 of the ground-water-flow model and subject to the same recharge, evaporation, and transpiration as the rest of layer 1 (fig. 13*A*). The hydraulic conductivity in the wetlands zone was estimated to be 7,344 ft/d (using MODFLOWP's parameter estimation). The hydraulic conductivity of wetlands is difficult to measure directly. This value is much too high to represent the hydraulic conductivity of the wetland materials (peat and muck), but rather reflects the fact that most of the water moves over this material and the wetlands act more like a pond than part of the ground-water system. The fourth zone consists of till. The exact value of hydraulic conductivity of the till had very little influence on model results because the till is of limited areal extent, has a very low hydraulic conductivity, and no measured head observations. The hydraulic conductivity of the till could not be estimated by non-linear regression and was set at 1 ft/d, an average value for till (Melvin and others, 1992). Horizontal hydraulic conductivities used in the ground-water model of the Usquepaug-Queen stratified-drift aquifer are shown in figures 13*A–C*.

The vertical hydraulic conductivity in stratified-drift aquifers commonly is proportional to, but usually much lower than, the horizontal hydraulic conductivity. Therefore, the vertical to horizontal anisotropy (the ratio of the vertical hydraulic conductivity to the horizontal hydraulic conductivity) can be an important factor affecting ground-water flow. The Usquepaug-Queen model was not sensitive to variations in anisotropy, however, and the model was calibrated to steady-state conditions primarily using shallow ground-water-level measurements. Data for hydraulic head at depth or during pumping conditions might better define the anisotropy. The vertical hydraulic conductivities were set to 1 ft/d in the wetlands, 10 ft/d in sand and gravel, and 0.1 ft/d in lake-bottom sediments. This is about one-tenth the horizontal hydraulic conductivities for these materials, which is typical for similar aquifers in the area (Dickerman, 1984).

Streambed material commonly is quite distinct from the glacial material it overlies because it has been eroded from upstream and redeposited on the streambed. Although streambed materials make up only a small part of the hydrologic system, they may be important because much of the discharge from the aquifer must flow through these materials. In this case, varying streambed hydraulic conductivity had minimal effect on the model. This may be the result of having extensive wetlands along streambanks. These wetlands provide an alternative path for the flow of water into and out of the aquifer, which may make the hydraulic conductivity of the streambed less important. Streambed hydraulic conductivity was set at 1.5 ft/d, slightly greater than the vertical hydraulic conductivity of the wetlands but less than that of the sand and gravel.

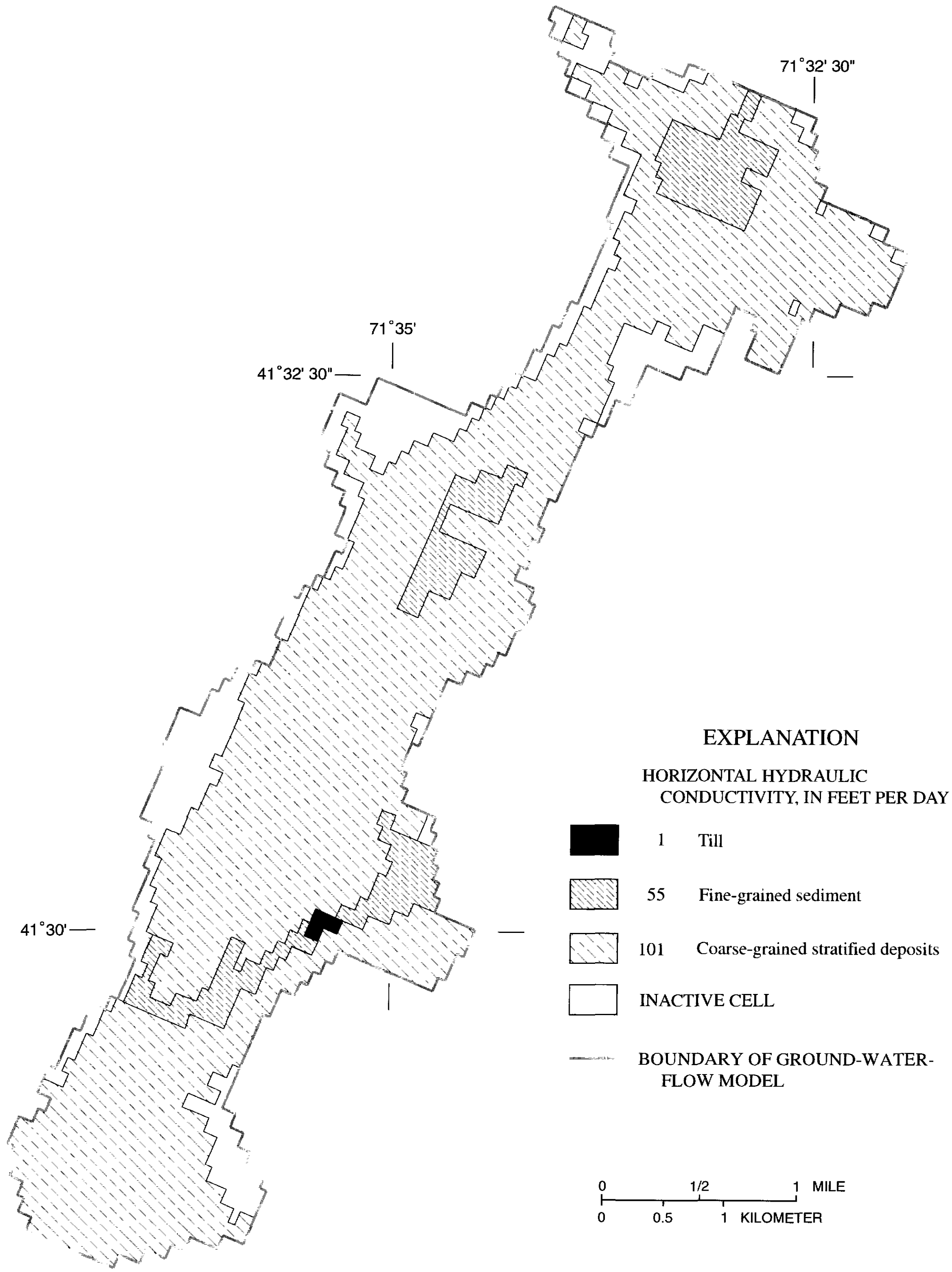
Accuracy of the Model

This model is intended to simulate the natural aquifer system. Therefore, ground-water levels and streamflows should match those measured in the field, and in general they do. Water levels from 24 observation wells were used to check the accuracy of the calibration of the ground-water-flow model. Differences between simulated and measured water-table altitudes at the 24 wells used for calibration ranged from 2.65 ft to -3.31 ft (table 6). The **mean** absolute error of these differences is 1.24 ft, and the root mean square error is 1.68 ft, which is small considering the overall variation of head in the aquifer is more than 100 ft (fig. 3). These errors appear to be distributed randomly throughout the model area. The spatial distribution or differences between simulated and measured water levels are shown in figure 12 for the calibrated steady-state model. The simulated streamflows on the Usquepaug and Queen Rivers were close to actual field measurements; the flow in the Queen River at Liberty Road was simulated to be 20.0 ft^3/s and measured to be 20.4 ft^3/s; and the flow in the Usquepaug River at State Highway 2, where the river leaves the basin, was simulated to be 42.2 ft^3/s and measured at 41.7 ft^3/s.



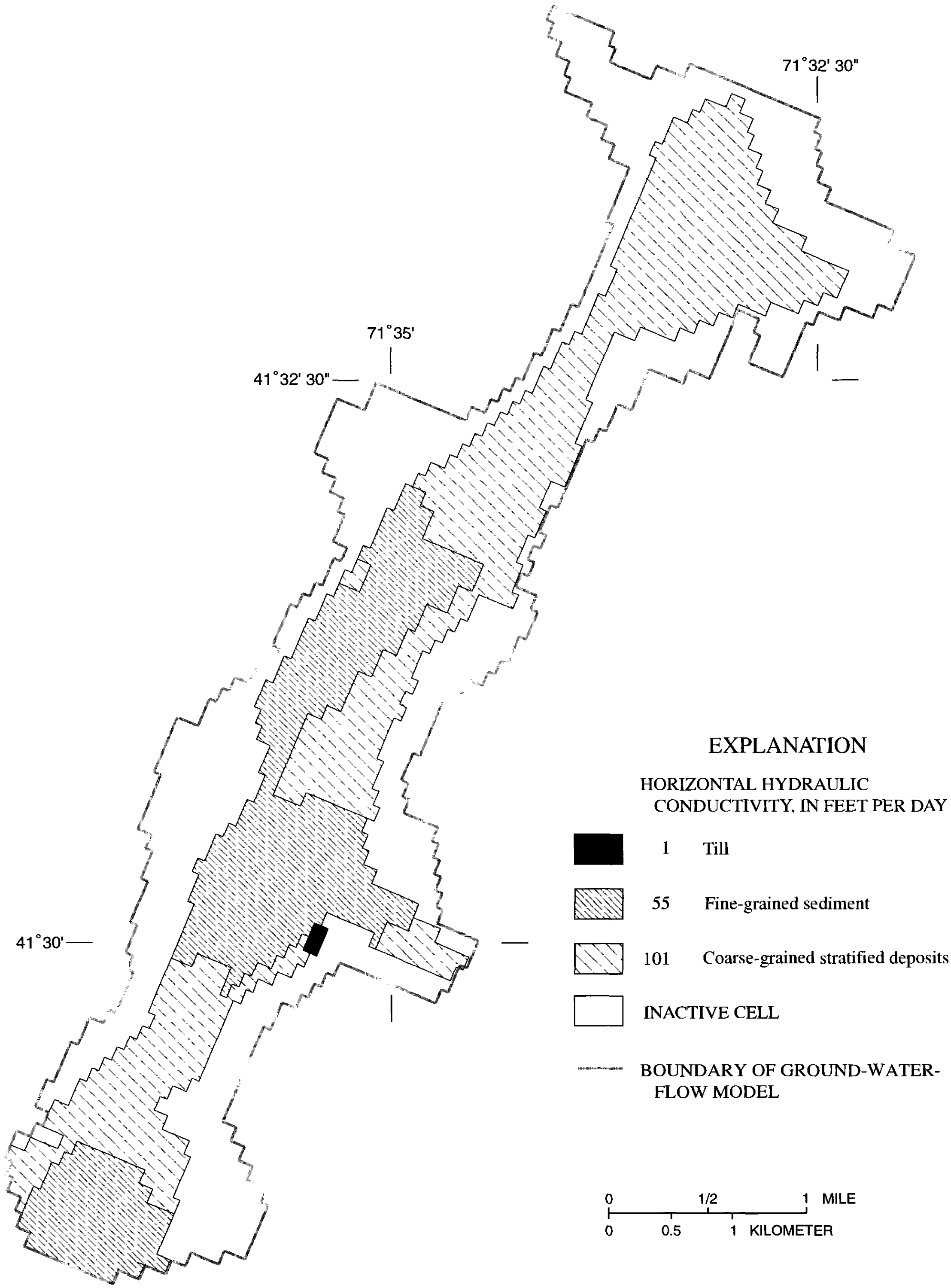
A. Layer 1

Figure 13. Horizontal hydraulic conductivity for layers 1, 2, and 3 used in the ground-water model of the Usquepaug-Queen stratified-drift aquifer in the Usquepaug-Queen model area, southern Rhode Island. *A.* Layer 1. *B.* Layer 2. *C.* Layer 3.



B. Layer 2

Figure 13. ***—Continued.***



C. Layer 3

Figure 13.—*Continued.*

Table 6. Simulated and measured water-table altitudes for selected observation wells in the Usquepaug-Queen model area, southern Rhode Island, September 1989

[No., number]

Well No.	Model cell (row, column)	Water-table altitude, in feet above sea level		
		Simulated	Measured	Difference
EXW 16	9,54	142.74	145.30	-2.56
EXW 553	3,20	147.65	145.00	2.65
EXW 554	12,57	143.29	144.90	-1.61
EXW 555	17,44	132.88	132.90	-.02
EXW 556	27,34	121.89	125.20	-3.31
EXW 558	27,29	121.06	120.60	.46
EXW 559	27,31	120.67	122.40	-1.73
EXW 560	43,38	121.50	122.60	-1.10
EXW 561	16,35	127.32	129.10	-1.78
RIW 188	82,9	99.76	99.50	.26
RIW 780	89,14	101.46	100.30	1.16
RIW 782	89,25	99.33	98.40	.93
SNW 311	52,6	115.64	113.20	2.44
SNW 314	59,19	117.75	117.10	.65
SNW 515	77,20	99.63	101.40	-1.77
SNW 1192	56,37	121.13	119.40	1.73
SNW 1193	59,32	120.16	118.60	1.56
SNW 1194	55,16	118.24	117.40	.84
SNW 1195	64,27	114.23	111.90	2.33
SNW 1196	64,20	113.73	113.10	.63
SNW 1197	67,8	108.52	108.20	.32
SNW 1198	73,24	104.49	104.80	-.31
SNW 1199	87,32	94.08	95.60	-1.52
SNW 1200	76,16	98.79	100.80	-2.02

The final step in the model calibration was to determine whether simulated steady-state inflows and outflows of water to the model area were in balance. The mass-balance calculation checks the numerical accuracy of the model solution and should be less than 0.1 percent (Konikow, 1978). The Usquepaug-Queen model had a mass-balance discrepancy of 0.02 percent, indicating that errors in numerical computations were not significant.

The simulated ground-water budget indicates that the source of recharge (inflow) to the stratified-drift aquifer is 14.9 ft^3/s (48 percent) direct precipitation, 8.5 ft^3/s (27 percent) ground-water inflow from the till/bedrock uplands, and 7.8 ft^3/s (25 percent) stream infiltration from naturally losing stream reaches under average annual nonpumping conditions. Most water, 27.8 ft^3/s (89 percent), was discharged to streams and the remaining 3.3 ft^3/s (11 percent) was lost to evapotranspiration.

SIMULATION OF GROUND-WATER-DEVELOPMENT ALTERNATIVES

Ground-water pumpage from the Usquepaug-Queen ground-water reservoir was simulated for **steady average** (1975–90) and drought (1963–66) conditions. The objective of pumping simulations was to evaluate the possible effects of various ground-water development alternatives on the ground-water levels, streamflow, and wetland-water levels in the basin. The model was used to simulate the interaction between surface water and ground water in the stream-wetland-aquifer system. Twelve sites were selected for simulation of pumping (table 7). These sites were chosen because lithologic logs or aquifer test data indicates that these areas could support large-capacity supply wells. For modeling purposes, all withdrawals were assumed to be exported from the model area to simulate what would occur if wells were tied into a regional water-supply system. If water withdrawn from the aquifer is returned to the flow system (for example, through septic systems) upstream from withdrawal points, water table and streamflow declines will be less than those predicted by the model. Locations of simulated pumping wells are shown on plate 1.

Ground-Water Pumping for Average Conditions

Nine development alternatives were simulated for average conditions (1975–90). Total pumpage ranged from 4 to 11 Mgal/d. Pumping more than 11 Mgal/d caused layer 1 of the model (including all the wetlands) to go dry. This created computational problems for the model and complete results could not be obtained. Various combinations of wells were used to determine the importance of the number and location of wells and to evaluate the effect of pumping on the stream-wetland-aquifer system.

Table 7. Selected ground-water-development alternatives simulated under steady-state conditions in the Usquepaug-Queen model area, southern Rhode Island

[No., number]

Well No.	Model cell (row, column)	Development alternatives (pumpage, in million gallons per day)										
		Average condition									Drought condition	
		1	2	3	4	5	6	7	8	9	10	11
EXW 39	6,44	--	--	1.5	0.5	--	0.5	0.5	0.5	1.0	--	1.5
EXW 416	6,47	1.0	0.5	--	.5	1.0	1.0	1.0	1.0	.5	1.0	--
EXW 33	9,55	--	.5	--	.5	--	.5	.5	.5	.5	--	--
EXW 565	16,41	--	.5	--	.5	1.0	1.0	1.0	1.0	1.0	--	--
EXW 401	27,31	1.0	.5	1.5	.5	1.0	.5	.5	1.0	1.0	1.0	1.5
EXW 571	32,25	--	.5	--	.5	1.0	1.0	1.0	1.0	1.0	--	--
EXW 573	34,23	--	--	--	.5	--	.5	.5	.5	1.0	--	--
SNW 1204	51,22	1.0	.5	1.5	.5	1.0	.5	1.0	1.0	1.0	1.0	1.5
SNW 908	55,17	--	.5	--	.5	1.0	.5	.5	1.0	1.0	--	--
SNW 1210	56,20	--	--	--	.5	--	.5	1.0	1.0	1.0	--	--
SNW 906	80,20	--	--	--	.5	--	.5	.5	.5	1.0	--	--
RIW 336	82,16	1.0	.5	1.5	.5	1.0	1.0	1.0	1.0	1.0	1.0	1.5
Total pumpage		4.0	4.0	6.0	6.0	7.0	8.0	9.0	10.0	11.0	4.0	6.0

Simulated pumping of 4 Mgal/d from four and eight wells (table 7) were used in development alternatives 1 and 2. Pumping four wells produced **drawdowns** in the corresponding model cells that ranged from 5.6 ft at well EXW 401 to 20.3 ft at well EXW 416. By spreading pumpage throughout the basin, withdrawals from eight wells showed declining drawdowns at pumped cells that ranged from 2.7 ft at well EXW 571 to 12.8 ft at well EXW 33. Drawdown given at a pumped-well cell is the average drawdown over the entire area of the cell (200 by 400 ft). Drawdown at a pumped well in the natural system would be greater than that for the simulated pumped-well cell, and would depend on the construction of the well. Total streamflow gain for all streams in the model area was reduced to 14.1 ft^3/s in alternatives 1 and 2, a 30-percent reduction from the nonpumping streamflow gain of 20.1 ft^3/s.

Simulated pumping of 6 Mgal/d from 4 and 11 wells (table 7) were used in development alternatives 3 and 4. Pumping four wells produced drawdowns in the corresponding model cells that ranged from 4.8 ft at well EXW 39 to 11.7 ft at well RIW 336. Pumping 11 wells produced drawdowns in the corresponding model cells that ranged from 0.2 ft at well EXW 39 to 13.1 ft at well EXW 33, a greater range than pumping from four wells. Total streamflow gain for all streams in the model area was reduced to 11.2 ft^3/s in alternatives 3 and 4, a 44-percent reduction from the nonpumping streamflow gain.

Simulated pumping of 7, 8, and 9 Mgal/d (table 7) were used in development alternatives 5, 6, and 7. Alternative 5 used 7 wells while 6 and 7 used 11 wells. Pumping 7 Mgal/d produced drawdowns in the corresponding model cells that ranged from 5.6 ft at wells EXW 401 and EXW 571 to 20.5 ft at well EXW 416. Total streamflow gain for all streams in the model area was reduced to 9.7 ft^3/s in alternative 5, a 52-percent reduction from the nonpumping streamflow gain. Pumping 8 Mgal/d produced drawdowns in the corresponding model cells that ranged from 0.6 ft at well SNW 906 to 26.0 ft at well EXW 416. Total streamflow gain for all streams in the model area was reduced to 8.1 ft^3/s in alternative 6, a 60 percent reduction from the nonpumping streamflow gain. Pumping 9 Mgal/d produced drawdowns in the corresponding model cells that ranged from 0.7 ft at well SNW 906 to 26.0 ft at well EXW 416. Total streamflow gain for all streams in the model area was reduced to 6.7 ft^3/s in alternative 7, a 67-percent reduction from the nonpumping streamflow gain.

Simulated pumping of 10 and 11 Mgal/d (table 7) were used in development alternatives 8 and 9. Pumping 10 Mgal/d produced drawdowns in the corresponding model cells that ranged from 0.7 ft at well SNW 906 to 26.0 ft at well SNW 908. Total streamflow gain for all streams in the model area was reduced to 5.3 ft^3/s in alternative 8, a 74-percent reduction from the nonpumping streamflow gain. Pumping 11 Mgal/d produced drawdowns in the corresponding model cells that ranged from 1.2 ft at well SNW 906 to 27.4 ft at well SNW 908. Total streamflow gain for all streams in the model area was reduced to 3.7 ft^3/s in alternative 9, a 82-percent reduction from the nonpumping streamflow gain. Under average conditions, pumping more than 11 Mgal/d caused the top layer of the model (including all wetlands) to go dry.

In general, higher pumping rates produced greater drawdowns than did lower pumping rates. Also, drawdowns generally can be reduced by distributing the total pumping over many wells. Boundary conditions also affect drawdowns. Drawdown were less than 1.3 ft in well SNW906, which was near a major stream (recharge boundary), and drawdowns were substantial, at least 12 ft, in well EXW33, which was near the edge of the model aquifer boundary (barrier boundary). These examples show that the effect on ground-water levels for a given amount of pumpage depends largely on the location of the pumping well relative to the aquifer boundaries. Total streamflow gains were not affected by the location of wells; however, the amount of water derived from induced infiltration of streamflow varies significantly relative to well location.

Ground-Water Pumping for Drought Conditions

The model also was used to evaluate the effects of pumping on the aquifer during simulated drought conditions. Drought conditions were simulated by reducing recharge from precipitation, inflow from till-covered bedrock uplands, and streamflow by 25 percent. This reduction approximates the 1963–66 drought, a period considered representative of extreme drought conditions in Rhode Island. The 1963–66 drought represents the lowest four consecutive years of annual precipitation recorded at the National Weather Service Station at Kingston since the station began operation in 1889.

Simulated pumping of 4 and 6 Mgal/d from four wells (table 7) were used in development alternatives 10 and 11. Pumping 4 Mgal/d produced drawdowns (relative to average annual water levels) in the corresponding model cells that ranged from 5.7 ft at well EXW 401 to 22.4 ft at well EXW 416, only 2 to 10 percent more than in alternative 1, in which the same number of wells were pumped. Total streamflow gain for all streams in the model area was decreased to 8.6 ft^3/s in alternative 10, a 39-percent reduction from the streamflow gain in alternative 1. Pumping 6 Mgal/d produced drawdowns in the corresponding model cells that ranged from 5.4 ft at well EXW 39 to 12.4 ft at well RIW 336. The drawdowns were less in alternative 11 because well EXW 39, which is farther from the aquifer boundary, was used instead of well EXW 416. This illustrates how pumpage can be increased and at the same time the effect on ground-water can be reduced by changing the location of pumping wells. Total streamflow gain for all streams in the model area was reduced to 5.7 ft^3/s in alternative 11, a 49-percent reduction from the streamflow gain in alternative 3 which pumped the same amount from four wells. Under drought conditions, pumping more than 6 Mgal/d caused layer 1 of the model (including all wetlands) to go dry. In general, pumping during simulated drought conditions increased drawdowns fractionally and greatly reduced overall streamflow gains.

Stream-Aquifer Interaction

Pumpage from the Usquepaug-Queen stratified-drift aquifer causes infiltration of streamflow along stream segments simulated in the ground-water-flow model. Water induced from streams under simulated average pumping conditions (1975–90) results in decreases in stream discharge at the USGS gaging station on the Usquepaug River that range from about 6 ft^3/s when pumping 4 Mgal/d to 16 ft^3/s when pumping 11 Mgal/d. During drought simulations (1963–66), stream discharge along the Usquepaug River decreased from about 6 ft^3/s when pumping 4 Mgal/d to 9 ft^3/s when pumping 6 Mgal/d. Variations in simulated discharge profiles along stream cells in the Usquepaug-Queen River valley for wells pumping during development alternatives 1, 3, 6, and 9 for average conditions (1975–90) and development alternatives10 and 11 for drought conditions are shown in figure 14.

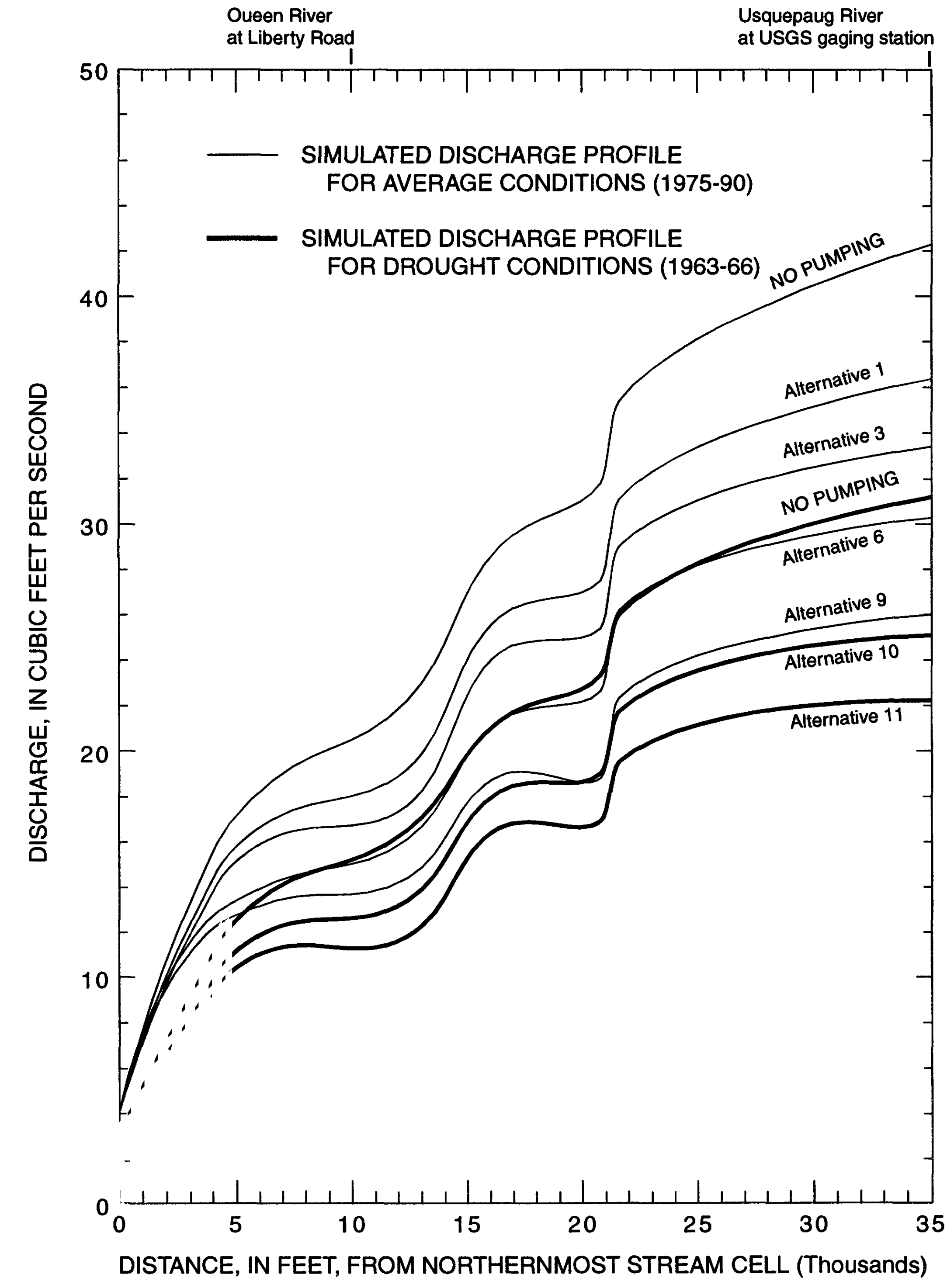


Figure 14. Variations in discharge profiles along stream cells in the Usquepaug-Queen River valley resulting from simulated pumping from wells under average and drought conditions in the Usquepaug-Queen River Basin, southern Rhode Island.

Predicted stream discharge profiles along the Usquepaug River when pumping 8 Mgal/d under average conditions (fig. 14) are similar to the profiles if no water is pumped under drought conditions. Predicted stream discharge profiles are similar for maximum simulated pumping of 11 Mgal/d (alternative 9) under average conditions and 4 Mgal/d (alternative 10) under drought conditions (fig. 14). No stream reaches went dry in the numerical model during any steady-state pumping simulation. Minimum streamflow at the USGS gaging station on the Usquepaug River near Usquepaug R.I. was maintained at 22 ft^3/s or more, well above the 7Q10 flow of 7.2 ft^3/s, during all pumping simulations. However, the effect of ground-water pumping on streamflow is most critical during summer months, when flow in streams generally is low. Using the lowest mean streamflow statistics from 1975 to 1990 for the Usquepaug River gaging station, pumping 3 Mgal/d (4.64 ft^3/s) or less from the Usquepaug-Queen ground-water reservoir should not cause streamflow to cease at the USGS gaging station on the Usquepaug River because measured streamflow is greater than simulated pumpage. However, pumping as much as 11 Mgal/d (17.0 ft^3/s) under average conditions could cause the flow at the gaging station to be very low or cease during some summer months in dry years for up to 90 consecutive days because simulated pumpage is greater than measured streamflow during some low-flow periods. Similarly, during drought conditions, pumping as much as 6 Mgal/d (9.28 ft^3/s) could cause streamflow at the USGS gaging station to be low or cease during summer months for periods as long as 30 consecutive days.

Wetlands-Aquifer Interaction

In the Usquepaug-Queen aquifer system, the wetlands act much as a lake would. Water flows easily across the top of the wetlands, which means that drawdowns from pumping tend to be spread out across a large area, as pumping water from one part of a lake draws down the whole lake by a small amount rather than drawing down the area nearest the pumping by a large amount. Also, most of the wetlands in the Usquepaug-Queen River Basin are well connected to streams and, therefore, water levels in the wetlands, especially near the stream, tend to remain constant even during pumping. The median drawdowns in the wetlands during average conditions ranged from 0.20 ft in alternative 1 (pumping 4 Mgal/d), to 0.28 ft in alternative 3 (pumping 6 Mgal/d), to 0.44 ft in alternative 9 (pumping 11 Mgal/d). Drawdowns were much larger in the wetlands during simulated drought conditions. The median drawdowns were 0.50 ft for alternative 10 (pumping 4 Mgal/d) and 0.67 ft for alternative 11 (pumping 6 Mgal/d), about 2.5 times the drawdown under average conditions. In general, drawdowns were much higher in isolated wetlands and very low in wetlands adjacent to streams. For example in alternative 5, the drawdown in node 11,59 (row, column) was 8.29 ft while the drawdown in node 39,14 was less than 0.01 ft. Node 11,59 is in an isolated wetland, which is only fed by an intermittent stream that is dry 75 percent of the time. Node 39,14 is on Locke Brook and flow is substantial at that node.

Source of Pumped Water

Water that is pumped from wells in the Usquepaug-Queen ground-water reservoir is derived from three sources: intercepted ground-water runoff, induced recharge from streamflow, and reduced evaporation and transpiration. The amount of water derived from each source is highly variable and depends on the distance between the well and the river. Generally, the closer a well is to a surface-water body, the larger the percentage of water derived from induced recharge from that surface-water body. The farther a well is from a surface-water body, the smaller the percentage of water derived through induced recharge and the greater the amount derived from intercepted ground-water runoff. Results of simulations of development alternatives show that 94 to 96 percent (table 8) of all ground-water pumped, under average annual (1975–90) or simulated drought (1963–66) conditions, would be derived primarily from intercepted ground-water runoff and induced stream infiltration. The remaining 4 to 6 percent (table 8) would be derived from reduced evaporation and transpiration.

Table 8. Source and relative percentages of water pumped from wells during selected ground-water-development alternatives in the Usquepaug-Queen River Basin, southern Rhode Island

[**Development alternative:** See table 7 for summary of data on individual pumping sites, pumping rates, and pumping conditions simulated. **Condition:** Average condition (1975-90) or simulated drought condition (1963-66). **Intercepted ground-water runoff:** Water that would have discharged into streams as ground-water runoff, but was intercepted by pumping wells before it reached the stream. Mgal/d, million gallons per day]

Development alternative	Condition	Number of wells pumping	Pumpage (Mgal/d)	Amount of water derived from given source (percentage of total pumpage)		
				Intercepted ground-water runoff	Induced recharge from the stream	Reduction in evaporation and transpiration
1	average	4	4.0	64	32	4
2	average	8	4.0	75	20	5
3	average	4	6.0	56	39	5
4	average	12	6.0	64	31	5
5	average	7	7.0	70	24	6
6	average	12	8.0	62	34	4
7	average	12	9.0	62	33	5
8	average	12	10.0	61	34	5
9	average	12	11.0	57	38	5
10	drought	4	4.0	56	40	4
11	drought	4	6.0	48	47	5

Results of simulation of development alternatives 1 through 9 for average conditions show that the source of water derived from intercepted ground-water runoff ranged from 56 to 75 percent (table 8) of the total water pumped. The amount of well water derived from induced recharge of streamflow ranged from 20 to 39 percent (table 8).

Simulation of development alternatives 10 and 11 for drought conditions show that the source of water derived from intercepted ground-water runoff ranged from 48 to 56 percent (table 8), and the amount from induced recharge of streamflow ranged from 40 to 47 percent (table 8). When comparing withdrawals for drought conditions (alternative 10 and 11) with average conditions (alternative 1 and 3), water derived from induced recharge from streams under similar pumping rates and number of wells increases 8 to 9 percent. Sources and relative percentages of water withdrawn from wells for selected development alternatives are summarized in table 8.

Delineation of Contributing Areas for Simulated Pumping Rates in the Stratified-Drift Aquifer

The risk of contaminating ground-water supplies may be reduced if areas that contribute water to wells can be delineated and these areas are then protected from land-use practices that could adversely affect the quality of the water. Estimates of areas in the stratified-drift aquifer that contribute water to institutional supply wells and simulated pumping wells in the Usquepaug-Queen River Basin were delineated for selected development alternatives by use of the particle-tracking algorithm MODPATH (Pollock, 1994). MODPATH computes ground-water pathlines on the basis of output from simulations using either MODFLOW or MODFLOWP. Areas that contribute water to wells were delineated only for the stratified-drift aquifer and do not show the part of the contributing area that would extend beyond the model boundary into the till and bedrock uplands.

In the Usquepaug-Queen ground-water-flow model, endpoint analyses were done on particles that were tracked forward (from the water table to a pumped well) in the direction of flow. In forward tracking, the contributing area of the well is defined by the area of the water table in which the particles that are captured by the pumped well originate. In this study, ground-water flow was accounted for by coding recharge, evapotranspiration, and stream packages used in MODFLOWP so that flows were assigned to the top face of cells. Pumped wells were treated as internal sinks and recharge wells (used to simulate lateral inflow from till and bedrock uplands) were coded so that MODPATH could search and apply flow across the correct cell face. Two particles were released instantaneously on the top face (face 6) of each cell (see Pollock, 1994) and the particles were allowed to pass through weak sink cells.

Contributing areas were estimated for all wells in each of 11 development alternatives simulated with the Usquepaug-Queen model. Estimated contributing areas for pumping wells simulated during three selected development alternatives are shown in figures 15–17. The configuration of individual contributing areas is related in part to the surface and subsurface distribution of coarse-grained (high hydraulic conductivity) and fine-grained (low hydraulic conductivity) material shown on the geologic materials map (pl. 1). Figure 15 shows areas in the stratified-drift aquifer that contribute water to four wells each pumping 1 Mgal/d (alternative 1), the minimum pumping rate simulated with the numerical model. Withdrawals for this ground-water-development alternative were spread evenly throughout the basin. For comparison, figure 16 shows how much of the basin can become a contributing area to wells in the stratified-drift aquifer if total pumpage is increased by 7 Mgal/d and the number of pumping wells is increased by eight wells (alternative 9). Figure 16 shows areas in the stratified-drift aquifer that contribute water to 12 pumping wells, 10 wells each pumping 1 Mgal/d and two wells each pumping 0.5 Mgal/d. Total pumpage for this development alternative was 11 Mgal/d, the maximum simulated with the numerical model.

Figure 17 shows estimated areas in the stratified-drift aquifer that contribute water to four wells pumping a total of 4 Mgal/d under simulated drought conditions (1963–66). The large increase in size of the contributing area in the northern part of the basin (fig. 17) is of particular interest, when compared to the contributing area for wells pumping 4 Mgal/d (alternative 10) under average conditions shown in figure 15. The increase in the size of the contributing area for this drought simulation probably is the result of the thinning of the stratified deposits in the northern part of the modeled area.

The areal extent of contributing areas delineated for selected simulated pumping wells using MODPATH suggest that large areas of the stratified-drift aquifer may need to be protected from land-use practices that could adversely affect the quality of the water in the Usquepaug-Queen ground-water reservoir.

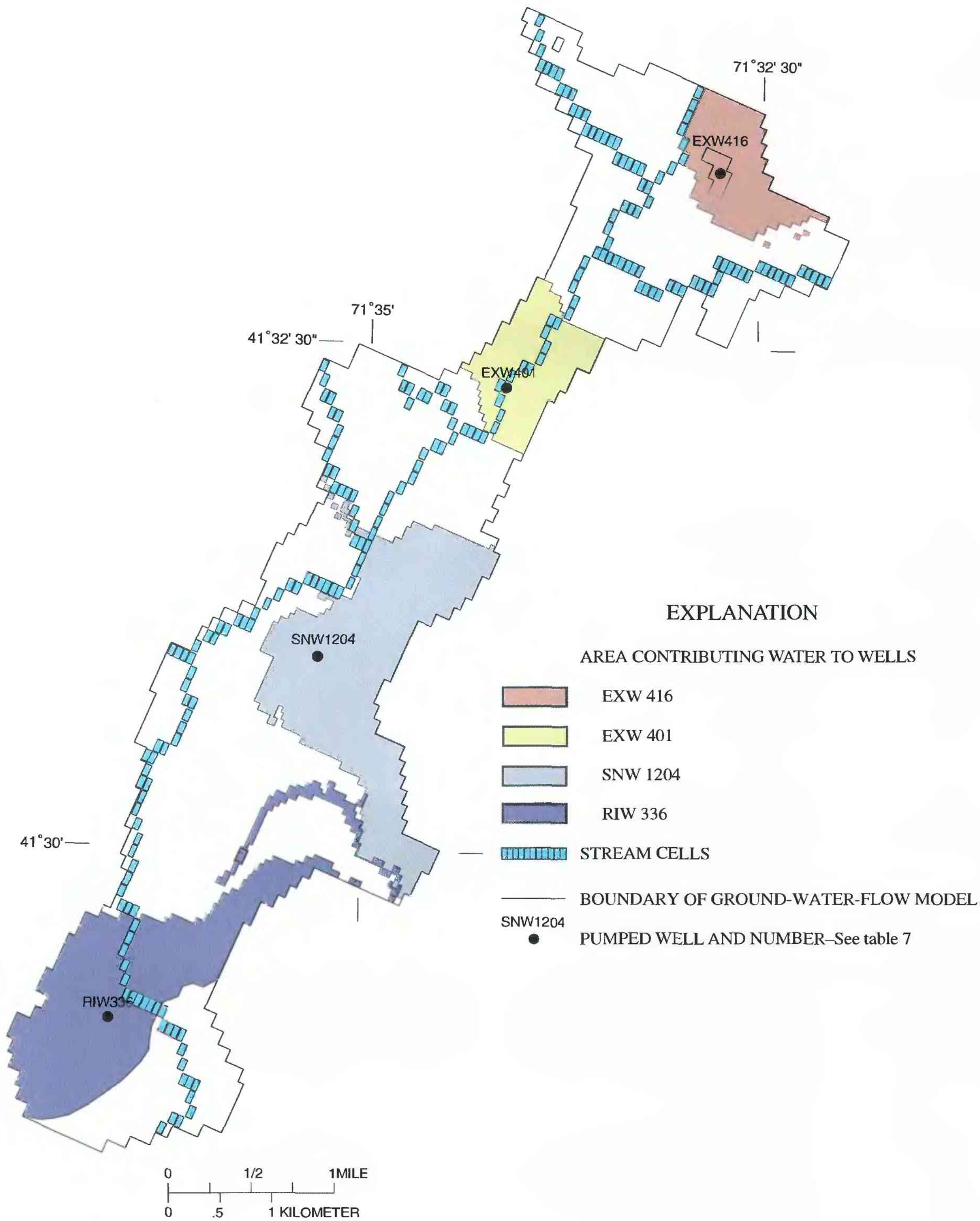


Figure 15. Estimated areas in the stratified drift contributing water to wells pumping 4 million gallons per day during average conditions in the Usquepaug-Queen model area, southern Rhode Island.

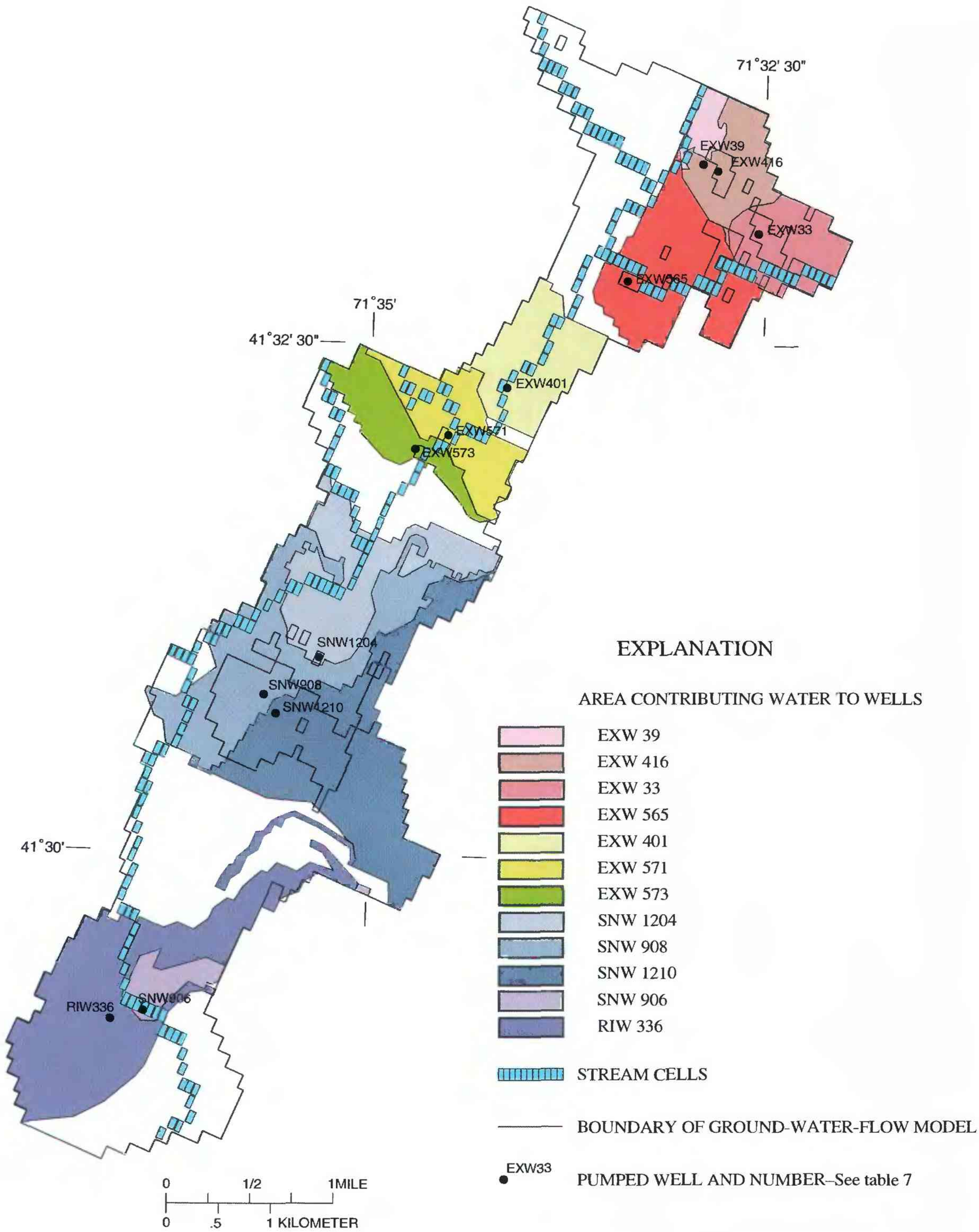


Figure 16. Estimated areas in the stratified drift contributing water to wells pumping 11 million gallons per day during average conditions in the Usquepaug-Queen model area, southern Rhode Island.

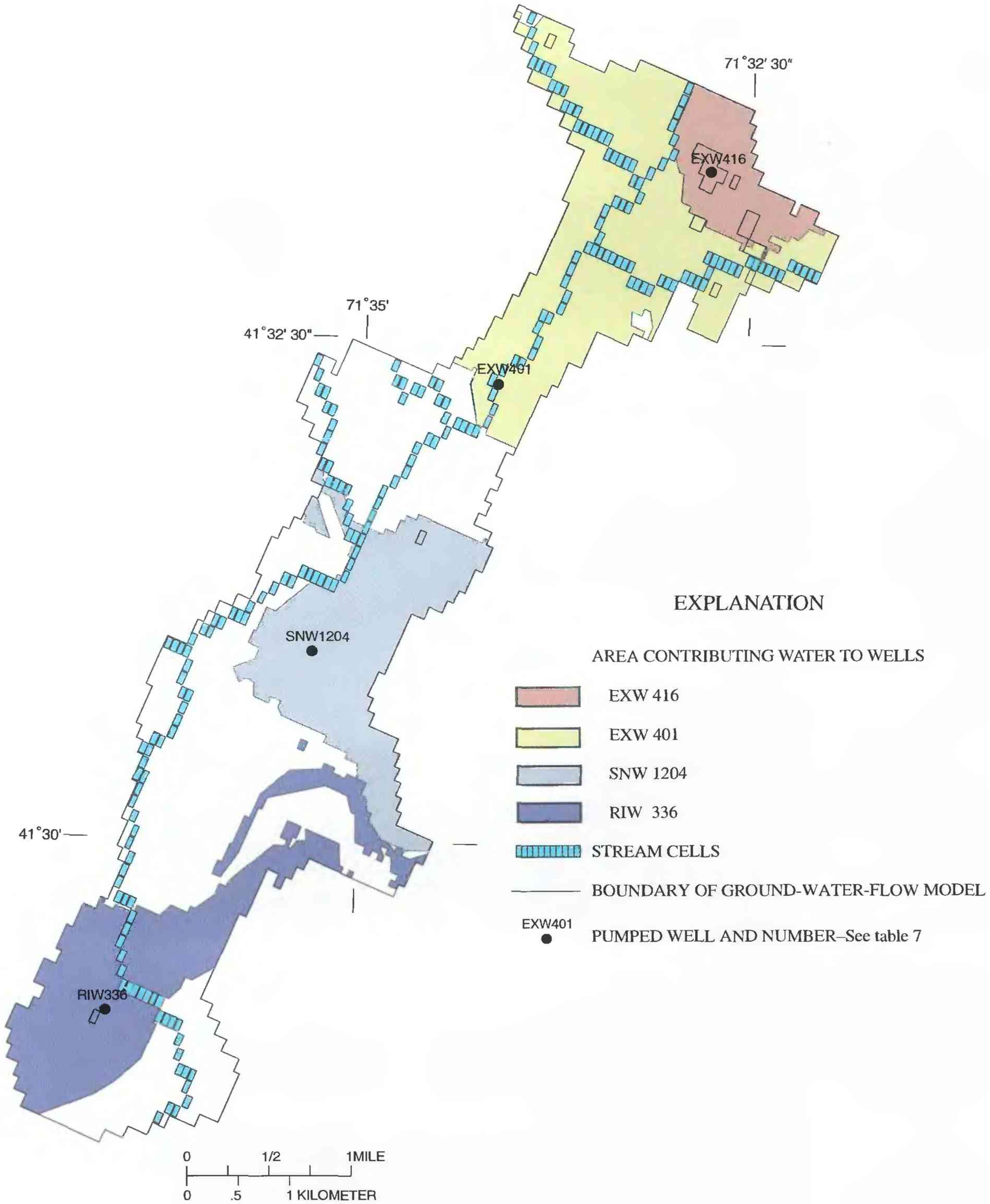


Figure 17. Estimated areas in the stratified drift contributing water to wells pumping 4 million gallons per day during drought conditions in the Usquepaug-Queen model area, southern Rhode Island.

SUMMARY AND CONCLUSIONS

Thick and areally extensive deposits of saturated coarse-grained stratified drift form the major and most productive aquifer in the Usquepaug-Queen River Basin. The stratified-drift aquifer is the only aquifer in the basin capable of producing yields of 0.5 Mgal/d or more from individual wells. The transmissivity of the stratified-drift aquifer determined from aquifer tests ranges from 4,000 to 26,200 ft^2/d, with a median of 11,400 ft^2/d. The horizontal hydraulic conductivity determined from the aquifer tests ranges from 53 to 330 ft/d, with a median of 134 ft/d. For comparison, the transmissivity estimated from lithologic logs ranges from 1,900 to 27,800 ft^2/d, with a median of 7,100 ft^2/d, and the horizontal hydraulic conductivity ranges from 25 to 470 ft/d, with a median of 120 ft/d.

Pumping from ground-water and surface-water sources in the Usquepaug-Queen River Basin averaged 0.28 Mgal/d during 1989 and 0.48 Mgal/d during 1990. About 57 percent (0.16 Mgal/d) of the average pumping during 1989 was derived from ground-water sources and 43 percent (0.12 Mgal/d) was derived from surface-water sources. About 44 percent (0.21 Mgal/d) of the average pumpage during 1990 was derived from ground-water sources and 56 percent (0.27 Mgal/d) was derived from surface-water sources. Irrigation, the largest single use of water in the Usquepaug-Queen River Basin is primarily pumped from surface-water sources and accounted for 43 percent of the average pumpage during 1989, and 64 percent of the average pumpage during 1990. The average annual rate of pumping for irrigation use was 0.12 Mgal/d during 1989 and 0.3 Mgal/d during 1990. However, irrigation water was pumped only during the growing season from June to September each year. Therefore, actual monthly rates of pumping are much higher than the average annual rates, and averaged 0.37 Mgal/d during the 1989 growing season and 0.90 Mgal/d during the 1990 growing season.

Ground water and surface water derived primarily from ground-water runoff in the Usquepaug-Queen River Basin are suitable for most purposes on the basis of the analysis of physical properties and chemical constituents. Ground water in the basin is somewhat corrosive, with the hydrogen-ion concentration or pH ranging from 3.9 to 6.5 with a median of 5.1. Specific conductance and concentrations of dissolved chloride and sodium, and total nitrogen exceed the USEPA maximum contaminant level (MCL) for public drinking water in some parts of the ground-water reservoir. Specific conductance of water in 21 wells not near roads ranged from 44 to 191 µS/cm, with a median of 75 µS/cm. Specific conductance of water in 13 wells near roads ranged from 54 to 495 µS/cm, with a median of 232 µS/cm.

Concentrations of dissolved chloride ranged from 7.2 to 210 mg/L in monthly water samples from monitoring wells, and from 3.8 to 73 mg/L, with a median of 8.9 mg/L in 34 wells sampled throughout the Usquepaug-Queen River Basin during August 9–17, 1993. Dissolved chloride in monitoring wells along State Highway 2 in the stratified-drift aquifer are considerably higher than the basin median of 8.9 mg/L. The high dissolved chloride in monitoring wells probably is due to the application of de-icing salts to road surfaces.

Concentrations of dissolved nitrogen in ground water in the Usquepaug-Queen River Basin were high as indicated by the median dissolved nitrogen of 1.06 mg/L for 34 samples. However, dissolved nitrogen concentrations in four monitoring wells exceeded the USEPA MCL of 10 mg/L, and ranged from 10 to 21 mg/L. These wells were part of a series of nine wells installed downgradient from turf fields. Total nitrogen concentrations from 115 samples analyzed in monitoring wells ranged from 0.3 to 29 mg/L. The high total nitrogen in these wells probably is due to the application of fertilizer to commercially cultivated turf fields.

The effects of selected ground-water development alternatives on ground-water levels, wetland-water levels, and streamflow in the Usquepaug-Queen ground-water reservoir were evaluated by means of a three-layer ground-water-flow model. The model was used to simulate the interaction between surface water and ground water in the stream-wetland-aquifer system. Steady-state simulations of hypothetical ground-water pumpage were made for average annual (1975–90) and drought (1963–66) conditions. The objective of the simulations was to evaluate the possible effects of a variety of development alternatives on the ground-water levels, streamflow, and wetland-water levels in the basin.

In general, higher pumping rates produced greater drawdowns than did lower pumping rates. Also, drawdowns generally can be reduced by distributing the total pumpage over many wells. Boundary conditions also affect drawdowns. Drawdowns were minimal (less than 1.3 ft) in a well near a major stream (recharge boundary), and drawdowns were substantial (at least 12 ft) in a well near the edge of the model aquifer boundary (barrier boundary). These examples show that the impact on ground-water levels for a given amount of pumpage depends primarily on the location of the pumping well relative to the aquifer boundaries. Total streamflow gains were not affected by the location of wells, however, and the amount of water derived from induced infiltration of streamflow varies significantly. In general, pumping during drought conditions increased drawdowns fractionally more than during average conditions, and greatly reduced overall streamflow gains.

Using the lowest mean streamflow statistics from 1975 to 1990 for the Usquepaug River gaging station, pumping 3 Mgal/d (4.64 ft^3/s) or less from the Usquepaug-Queen ground-water reservoir should not cause streamflow to cease at the USGS gaging station on the Usquepaug River because measured streamflow is greater than simulated pumping. However, pumping as much as 11 Mgal/d (17.0 ft^3/s) under average conditions could cause the flow at the gaging station to be low or to cease during some summer months in dry years for as many as 90 consecutive days, because simulated pumping is greater than measured streamflow during some low-flow periods. Similarly, during drought conditions, pumping as much as 6 Mgal/d (9.28 ft^3/s) could cause streamflow at the USGS gaging station to be low or to cease during summer months for periods as long as 30 consecutive days. Most of the wetlands in the Usquepaug-Queen River Basin are hydraulically well connected to streams and, therefore, water levels in the wetlands, especially near the stream, tend to be kept constant even during pumping. Drawdowns were much larger in the wetlands during simulated drought conditions. The median drawdowns were 0.50 ft for alternative 10 (pumping 4 Mgal/d) and 0.67 ft for alternative 11 (pumping 6 Mgal/d), about 2.5 times the drawdown under average conditions. In general, drawdowns were much higher in isolated wetlands and low in wetlands adjacent to streams.

Results of simulations of selected development alternatives show that 94 to 96 percent of all ground-water pumped, under average annual (1975–90) or simulated drought (1963–66) conditions, would be derived primarily from intercepted ground-water runoff and induced stream infiltration. Simulation of development alternatives for average conditions show that the source of water derived from intercepted ground-water runoff ranged from 56 to 75 percent and that derived from induced recharge of streamflow ranged from 20 to 39 percent. For drought conditions, the source of water derived from intercepted ground-water runoff ranged from 48 to 56 percent, and the amount from induced recharge of streamflow ranged from 40 to 47 percent. Estimates of areas in the stratified-drift aquifer that contribute water to existing supply wells and to hypothetical pumping wells in the Usquepaug-Queen River Basin were delineated for selected development alternatives by use of the particle-tracking algorithm MODPATH. Areas that contribute water to wells were delineated only for the stratified-drift aquifer and do not show the part of the contributing area that would extend beyond the model boundary into the till and bedrock uplands.

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GLOSSARY

Ablation till: A loose, sandy, commonly bouldery till formerly in or on glacial ice that accumulated in place as the ice melted (ablated).

Anisotropy: That condition in which some or all hydraulic properties vary with direction.

Aquifer: A formation, group of formations, or part of a formation that contains enough saturated permeable material to yield large quantities of water to wells and springs.

Aquifer test: A controlled field experiment wherein the effect of pumping a well is measured in the pumped well and in observation wells for the purpose of determining hydraulic properties of an aquifer.

Bedrock: The solid rock, locally called "ledge," that underlies unconsolidated material at the Earth's surface.

Conceptual model of the stream-aquifer system: A general idea or understanding of a stream-aquifer system that makes realistic mathematical simulation of that system possible.

Contact: A plane or irregular surface between two different types or ages of rocks or unconsolidated sediments.

Continuous-record streamflow-gaging station: A site on a stream at which continuous measurements of stream stage are made. These records are converted to daily flow after calibration by means of flow measurements.

Crystalline bedrock: An inexact but convenient term designating igneous or metamorphic rock, as opposed to **sedimentary bedrock**.

Discharge: The volume of water that passes a given point in a given period of time.

Dissolved solids: The residue from a clear sample of water after evaporation and drying for 1 hour at 180° Celsius; consists primarily of dissolved mineral constituents, but may also contain organic matter.

Drainage area: The drainage area of a stream at a specified location is that area, measured in a horizontal plane, which is enclosed by a drainage divide.

Drainage basin: A part of the surface of the earth that is occupied by a drainage system, which consists of a surface stream or a body of impounded surface water together with all tributary surface streams and bodies of impounded surface water.

Drawdown: The decline of water level in a well after pumping begins. It is the difference between the water level in a well after pumping begins and the water level as it would have been if the well had not been pumped.

Evaporation: The process by which water is changed from the liquid or solid state into the vapor state. In hydrology, evaporation is vaporization that takes place at a temperature below the boiling point.

Facies: The aspect, appearance, and characteristics of a rock or sediment unit, usually reflecting the condition of its origin; especially as differentiating the unit from adjacent or associated units.

Fissility: A general term for the property possessed by some rocks or sediments of splitting easily into thin layers along closely-spaced, roughly planar, and approximately parallel surfaces, such as bedding planes in shale or cleavage planes in schist.

Gaining stream: A stream or reach of a stream whose flow is being increased by inflow of ground water.

Gneiss: A coarse-grained rock in which bands rich in granular minerals alternate with bands in which schistose minerals predominate.

Granite: A plutonic rock consisting essentially of alkalic feldspar and quartz.

Ground-water discharge: Water that is released from the saturated zone in the ground. It includes leakage of water into stream channels, lakes, and oceans; evapotranspiration; and withdrawal from wells.

Ground-water drainage divide: A line on a water-table map on each side of which the water table slopes downward away from the line. It is analogous to a divide between two drainage basins on a land surface. Generally a ground-water drainage divide is found nearly below a surface-water drainage divide, but in some localities there is no relation between the two.

Ground-water outflow: That part of the discharge from a drainage basin that occurs through the ground. The term "underflow" is often used to describe ground-water outflow that takes place in valley-fill material (instead of the surface channel) and thus is not measured at a stream-gaging station.

Ground-water recharge: The amount of water that is added to the saturated zone.

Ground-water reservoir: That part of the sand and gravel aquifer in which transmissivity and saturated thickness are greatest and where ground water may be present in quantities suitable for development and use.

Ground-water runoff: That part of the runoff which has passed into the ground, has become ground water, and has been discharged into a stream channel as spring or seepage water.

Head: The height above a standard datum of the surface of a column of water (or other liquid) that can be supported by the static pressure at a given point.

Heterogeneity: Heterogeneity is synonymous with nonuniformity. A material is heterogeneous if its hydrologic properties are not identical everywhere.

Hydraulic conductivity: The volume of water at the existing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow. Hydraulic conductivity is expressed in cubic foot per day per square foot, or foot per day in reduced form (as used in this report).

Hydraulic gradient: The change in static head per unit of distance in a given direction. If not specified, the direction generally is understood to be that of the maximum rate of decrease in head.

Induced infiltration: The process by which water moves into an aquifer from an adjacent surface-water body, owing to reversal of the hydraulic gradient in response to pumping.

Induced recharge: The amount of water entering an aquifer from an adjacent surface-water body by the process of induced infiltration.

Kettle hole: A steep-sided, usually basin- or bowl-shaped hole or depression without surface drainage in glacial-drift deposits, often containing a lake or swamp, and believed to have formed by the melting of a large, detached block of stagnant ice (left behind by a retreating glacier) that had been wholly or partly buried in the glacial drift.

Lifetime health advisory: That concentration of the chemical in drinking water that is not expected to cause any adverse non-carcinogenic effects over a lifetime exposure with a margin of safety. Based on a 70 kilogram adult consuming 2 liters of water per day over a lifetime period of 70 years.

Lithologic log: Description of geologic material collected during sampling of test wells.

Lodgment till: A compact till commonly characterized by fissile structure and containing stones oriented with their long axes generally parallel to the direction of ice movement; deposited beneath active ice at the base of the ice sheet.

Losing stream: A stream or reach of a stream that is losing water to the ground.

Maximum contaminant level: Maximum concentration or level of a contaminant in drinking-water supplies as established by the U.S. Environmental Protection Agency and adopted by the Rhode Island Department of Health. Primary Maximum Contaminant Levels are based on health considerations and are legally enforceable. Secondary Maximum Contaminant Levels are based on esthetic considerations and are recommended guidelines.

Mean (arithmetic): The sum of the individual values of a set, divided by their total number, also referred to as the "average."

Median: The middle value of a set of measurements that are ordered from lowest to highest; 50 percent of the measurements are lower than the median, and 50 percent are higher.

Numerical model: A simplified mathematical representation of a complex aquifer system. A computer program designed to solve ground-water-flow equations.

pH: Symbol denoting the logarithm to base 10 of hydrogen-ion concentration in a solution. pH values range from 0 to 14. The lower the value, the more hydrogen ions the solution contains. A value of 7.0 is the neutral point; values greater than 7.0 indicate an alkaline solution; values less than 7.0 indicate an acid solution.

Preconditioned conjugate-gradient 2 (PCG2): A method for iteratively solving a large system of simultaneous linear equations.

Primary porosity: The property of a rock or unconsolidated material of containing voids or open spaces within the matrix of the material and expressed as the ratio of the volume of open space to total volume of the rock or material.

Runoff: Part of precipitation that appears in surface streams. It is the same as streamflow unaffected by artificial diversion, storage, or other works of man in or on stream channels. Includes both surface- and ground-water runoff.

Saturated thickness: The thickness of an aquifer below the water table. As measured for the stratified-drift aquifer in this report, it is the vertical distance between the water table and the bedrock surface; in places, it includes till between the stratified drift and the bedrock surface.

Scarp: A line of cliffs produced by faulting or by erosion. The term is an abbreviated form of escarpment, and the two terms commonly have the same meaning.

Sedimentary bedrock: A rock resulting from the consolidation of loose sediment that has accumulated in layers.

Seismic refraction: A geophysical method often useful for determining the depth to the water table and (or) bedrock. A seismograph is used to measure the time it takes for a compressional sound wave generated by an energy source to travel down through layers of the Earth and back up to detectors placed on the land surface.

Specific conductance: A measure of the ability of water to conduct an electrical current, expressed in microsiemens per centimeter at 25 degrees Celsius. Specific conductance is related to the type and concentration of ions in solution and can be used for estimating the dissolved-solids content of the water. Commonly, the concentration of dissolved solids (in milligrams per liter) is about 65 percent of specific conductance (in microsiemens per centimeter) at 25 degrees Celsius. This relation is not constant from stream to stream or from well to well, and it may even vary in the same source with changes in the composition of the water.

Specified flux: A fixed value of volumetric flow specified by recharge (or discharge) wells at appropriate cells to simulate flow across the boundary.

Steady state: Unchanging conditions during which aquifer storage and water levels do not vary with time. Steady-state conditions in this report are equated to average annual conditions for the period 1975–1990.

Stratified drift: (Also **stratified deposits**) Unconsolidated sediment that has been sorted by grain size by glacial meltwater and deposited in layers, or strata.

Stream-gaging station: A particular site on a stream, canal, lake, or reservoir where systematic observations of gage height or discharge are obtained.

Till: A geologic term for a glacial deposit of pre-dominantly nonsorted, nonstratified material ranging in size from boulders to clay. It is commonly so compact that it is difficult to penetrate with light drilling equipment.

Transmissivity: The rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of the aquifer under a unit hydraulic gradient. It is equal to the product of the hydraulic conductivity and saturated thickness. It is reported as cubic foot per day per square foot times foot of aquifer thickness, which reduces to square foot per day (as used in this report).

Transpiration: The process by which water vapor escapes from living plants, principally the leaves, and enters the atmosphere.

Unconfined (water-table) aquifer: An aquifer in which the upper surface of the saturated zone, the water table, is at atmospheric pressure and is free to rise and fall.

Underflow: See **Ground-water outflow.**

Water table: Surface in an unconfined water body at which the pressure is atmospheric. Material below the water table is saturated.

Zero-flux or no-flow boundary: A model boundary condition that is specified by assigning a value of zero transmissivity to nodes outside the boundary to simulate no flow across the boundary.