# Simulation of Ground-Water Flow and Areas Contributing Recharge to Production Wells in Contrasting Glacial Valley-Fill Settings, Rhode Island

By Paul J. Friesz and Janet R. Stone

Prepared in cooperation with the Rhode Island Department of Health

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# Contents

Abstract ....1
Introduction ....2
    Purpose and Scope ....2
    Description of Study Sites and Previous Investigations ....2
Numerical Modeling ....4
    Hydraulic Properties ....5
    Recharge Rates ....5
Harrisville Study Site ....5
    Geology ....7
    Hydrology ....9
    Ground-Water-Flow Model ....15
        Model Design ....15
        Simulation of Ground-Water Flow ....19
        Areas Contributing Recharge to Production Wells ....20
        Sensitivity and Uncertainty Analysis ....25
Richmond Study Site ....29
    Geology ....29
    Hydrology ....32
    Ground-Water-Flow Model ....33
        Model Design ....34
        Simulation of Ground-Water Flow ....37
        Areas Contributing Recharge to Production Wells ....39
        Sensitivity and Uncertainty Analysis ....42
Summary and Conclusions ....46
Acknowledgments ....47
References Cited ....48

## Figures


1–4. Maps showing—

1. Study sites in Rhode Island and selected U.S. Geological Survey (USGS) long-term network streamflow-gaging stations and observation wells, and National Oceanic and Atmospheric Administration (NOAA) climatological stations ...............3
2. Production wells, section lines, selected borings and observation wells, model extent, and surficial geology, Harrisville study site, Rhode Island ...................6
3. Data-collection network near production wells and water levels on June 24, 2005, Harrisville study site, Rhode Island..........................................................8
4. Bedrock-surface contours, Harrisville study site, Rhode Island...............................10

5. Geologic cross sections (lines of sections A-A′ and B-B′ are shown in figure 2), Harrisville study site, Rhode Island ........................................................................11

6–7. Graphs showing—

6. Water levels measured in observation well BUW187, 1997–2006 Harrisville study site, Rhode Island.................................................................................................13
7. Paired surface-water altitudes and ground-water altitudes at selected streambed piezometers in Batty Brook, 2004–2006 Harrisville study site, Rhode Island ........................................................................................................14

8. Model-boundary types, recharge rates, simulated water-table contours for nonpumping, steady-state conditions, and spatial distribution of residuals (measured-simulated), Harrisville study site, Rhode Island...............................................17

9. Graph showing (*A*) Relation between simulated and measured ground-water levels and (*B*) residual (measured minus simulated) ground-water levels as a function of measured ground-water levels, Harrisville study site, Rhode Island............19

10–16. Maps showing...................................................................................................................

10. Simulated area contributing recharge to the Harrisville well field at its average pumping rate of 224 gallons per minute, Harrisville study site, Rhode Island ........................................................................................................21
11. Simulated area contributing recharge to the Harrisville well field at its maximum pumping rate of 600 gallons per minute, Harrisville study site, Rhode Island ........................................................................................................22
12. Simulated traveltimes to the Harrisville well field at its maximum pumping rate of 600 gallons per minute, Harrisville study site, Rhode Island...........................24
13. Sensitivity analysis of the effects of multiplying the vertical hydraulic conductivity of streambed sediments at the well-field site by 0.5 and by 2, Harrisville study site, Rhode Island.................................................................................26
14. Sensitivity analysis of the effects of multiplying the hydraulic conductivity of stratified deposits by 0.75 and by 1.25, Harrisville study site, Rhode Island .............27
15. Sensitivity analysis of the effects of multiplying recharge rates by 0.75 and by 1.25, Harrisville study site, Rhode Island ..................................................................28
16. Production wells, section lines, selected borings and observation wells, model extent, surficial geology, and bedrock-surface contours, Richmond study site, Rhode Island.................................................................................................30

17. Geologic cross sections showing Richmond study site, Rhode Island............................31

18. Model-boundary types, recharge rates, simulated water-table contours for nonpumping, steady-state conditions, and spatial distribution of residuals (measured-simulated), Richmond study site, Rhode Island ....36
19. Graphs showing (*A*) Relation between simulated and measured ground-water levels and (*B*) residual (measured minus simulated) ground-water levels as a function of measured ground-water levels, Richmond study site, Rhode Island ....38
20–24. Maps showing—
20. Simulated area contributing recharge to the Richmond well field at 337.5 gallons per minute, which is half of its maximum pumping rate of 675 gallons per minute, Richmond study site, Rhode Island ....40
21. Simulated area contributing recharge to the Richmond well field at its maximum pumping rate of 675 gallons per minute, Richmond study site, Rhode Island ....41
22. Simulated traveltimes to the Richmond well field at its maximum pumping rate of 675 gallons per minute, Richmond study site, Rhode Island ....43
23. Sensitivity analysis of the effects of multiplying the hydraulic conductivity of stratified deposits by 0.75 and by 1.25, Richmond study site, Rhode Island ....44
24. Sensitivity analysis of the effects of multiplying recharge rates by 0.75 and by 1.25,Richmond study site, Rhode Island ....45

# Tables

1. Characteristics of the production wells for the Harrisville and Richmond study sites, Rhode Island ....7
2. Streamflow and drainage-area characteristics of the Branch and Nipmuc River streamflow-gaging stations, Harrisville study site, Rhode Island ....13
3. Summary of the long-term mean annual streamflow analysis for the temporary streamflow-gaging stations upstream of the well-field site, Harrisville study site, Rhode Island ....16
4. Summary of simulated values for hydraulic properties and recharge rates in the ground-water-flow model for the Harrisville study site, Rhode Island ....16
5. Simulated steady-state average annual hydrologic budget for nonpumping conditions, Harrisville study site, Rhode Island ....20
6. Sizes of areas contributing recharge to the Harrisville production well field (Central Street) and the percentages of water withdrawn from different sources, Harrisville study site, Rhode Island ....23
7. Streamflow and drainage-area characteristics of selected streamflow-gaging stations in and near the Richmond study site, Rhode Island ....33
8. Summary of the long-term mean annual ground-water discharge analysis for partial-record sites, Richmond study site, Rhode Island ....34
9. Summary of simulated values for hydraulic properties and recharge rates in the ground-water-flow model for the Richmond study site, Rhode Island ....35
10. Simulated steady-state average annual hydrologic budget for nonpumping conditions, Richmond study site, Rhode Island ....38
11. Sizes of areas contributing recharge to the Richmond production well field and the percentages of water withdrawn from different sources, Richmond study site, Rhode Island ....39

# Conversion Factors, Datums, and Acronyms

| Multiply | By | To obtain |
|---|---|---|
| | Length | |
| inch (in.) | 2.54 | centimeter (cm) |
| foot (ft) | 0.3048 | meter (m) |
| mile (mi) | 1.609 | kilometer (km) |
| | Area | |
| square mile ($mi^2$) | 2.590 | square kilometer ($km^2$) |
| | Flow rate | |
| cubic foot per second ($ft^3/s$) | 0.02832 | cubic meter per second ($m^3/s$) |
| gallon per minute (gal/min) | 0.06309 | liter per second (L/s) |
| inch per year (in/yr) | 25.4 | millimeter per year (mm/yr) |
| | Hydraulic conductivity | |
| foot per day (ft/d) | 0.3048 | meter per day (m/d) |
| | Transmissivity | |
| foot squared per day ($ft^2/d$) | 0.09290 | meter squared per day ($m^2/d$) |

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

$$°C=(°F-32)/1.8$$

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

ABBREVIATIONS

| | |
|---|---|
| MTBE | methyl *tert*-butyl ether |
| RIDEM | Rhode Island Department of Environmental Management |
| RIDOH | Rhode Island Department of Health |
| USGS | U.S. Geological Survey |

# Simulation of Ground-Water Flow and Areas Contributing Recharge to Production Wells in Contrasting Glacial Valley-Fill Settings, Rhode Island

By Paul J. Friesz and Janet R. Stone

## Abstract

Areas contributing recharge and sources of water to a production well field in the Village of Harrisville and to a production well field in the Town of Richmond were delineated on the basis of calibrated, steady-state ground-water-flow models representing average hydrologic conditions. The study sites represent contrasting glacial valley-fill settings. The area contributing recharge to a well is defined as the surface area where water recharges the ground water and then flows toward and discharges to the well.

In Harrisville, the production well field is composed of three wells in a narrow, approximately 0.5-mile-wide, valley-fill setting on opposite sides of Batty Brook, a small intermittent stream that drains 0.64 square mile at its confluence with the Clear River. Glacial stratified deposits are generally less areally extensive than previously published. The production wells are screened in a thin (30 feet) but transmissive aquifer. Paired measurements of ground-water and surface-water levels indicated that the direction of flow between the brook and the aquifer was generally downward during pumping conditions. Long-term mean annual streamflow from two streams upgradient of the well field totaled 0.72 cubic feet per second.

The simulated area contributing recharge for the 2005 average well-field withdrawal rate of 224 gallons per minute extended upgradient to ground-water divides in upland areas and encompassed 0.17 square mile. The well field derived 62 percent of pumped water from intercepted ground water and 38 percent from infiltrated stream water from the Batty Brook watershed. For the maximum simulated well-field withdrawal of 600 gallons per minute, the area contributing recharge expanded to 0.44 square mile to intercept additional ground water and infiltration of stream water; the percentage of water derived from surface water, however, was the same as for the average pumping rate. Because of the small size of Batty Brook watershed, most of the precipitation recharge in the watershed was withdrawn by the well field at the maximum rate either by intercepted ground water or indirectly by infiltrated stream water. Because the production wells are screened in a thin and transmissive aquifer in a small watershed, simulated ground-water traveltimes from recharge locations to the discharging wells were relatively short: 93 percent of the traveltimes were 10 years or less.

In Richmond, the production well field is composed of two wells adjacent to and east of the Wood River in a moderately broad, approximately 1.2-mile-wide, valley-fill setting. The wells are screened in a transmissive aquifer with saturated thickness greater than 60 feet. Streamflow measurements in Baker Brook, a tributary to the Wood River 0.4 mile north of the well-field site, indicated that natural net loss of streamflow between the upland-valley contact and a downstream site was 0.12 cubic feet per second under average hydrologic conditions.

Simulated areas contributing recharge for the maximum well-field pumping rate of 675 gallons per minute and for one-half the maximum rate extended northeastward from the well field to ground-water divides in upland areas. The area contributing recharge also included a remote, isolated area on the opposite side of the Wood River from the well field. The model simulation indicated that the well field did not derive any of its water from the Wood River because of the large watershed and associated quantity of ground water available for capture by the well field.

The area contributing recharge for one-half the maximum rate was 0.31 square mile and the primary source of water to the well field was direct precipitation recharge. Fifteen percent of the water withdrawn from the production wells, however, was obtained from Baker Brook, indicating the importance of even small, distant tributary streams to the contributing area to a well. The area contributing recharge on the opposite side of the Wood River is a small upland till area. For the maximum pumping rate, the 0.66-square-mile area contributing recharge extended farther up and down the valley to intercept additional ground water and infiltration from Baker Brook; the percentage of pumped water derived from Baker Brook (10 percent), however, was less than for the lower pumping rate. The area contributing recharge across the Wood River included upland till and stratified deposits near the upland-valley contact. Because the Richmond well field is in a larger watershed with saturated sediments thicker than at the Harrisville site, the overall ground-water traveltimes are greater: only 54 percent of the traveltimes are 10 years or less.

Hydrologic factors that most affected the simulated areas contributing recharge to production wells in the two contrasting valley-fill settings were recharge rates, the locations of upgradient ground-water divides, aquifer transmissivity, and, depending on the setting, the hydraulic connection between surface water and the aquifer. A well in the vicinity of a surface-water source may not always induce flow from that source, even if surface and ground waters are well connected, because the amount of water that a well draws from surface water also depends on the pumping rate and the quantity of ground water that the well can intercept. The area contributing recharge to a well also may include areas on the opposite side of a river from the well, despite the fact that the river is a major source of water in close proximity to the well. Under pumping conditions, precipitation recharge originating on the opposite side of a river may pass beneath the river and discharge to the well, although there may be little or no induced infiltration of river water. Areas contributing recharge can also extend into upland areas to ground-water divides and can also include isolated areas remote from a well.

# Introduction

Accurate delineation of areas contributing recharge to production wells is an essential component of Federal, State, and local and strategies for the protection of drinking-water supplies from contamination (U.S. Environmental Protection Agency, 1991). The Source Water Assessment Program of the Rhode Island Department of Health (RIDOH), Office of Drinking Water Quality, was established by the 1996 Amendments to the Federal Safe Drinking Water Act. Since that time, RIDOH has assessed the susceptibility and risk of public-water supplies to contamination and encourages land-use planning within the areas contributing recharge to a production well. The Rhode Island Department of Environmental Management (RIDEM), Office of Water Resources, has determined areas contributing recharge to most production wells in Rhode Island, but the RIDEM and RIDOH do not have a high degree of confidence in some of the contributing areas delineated for wells in complex hydrologic settings. Numerical ground-water-flow modeling, coupled with a particle-tracking technique, is a more advanced method for delineating areas contributing recharge than the analytical methods that have previously been used for this purpose.

The Village of Harrisville well field (Central Street) is an important ground-water supply in northwestern Rhode Island (fig. 1). The RIDOH determined this well field, screened in a thin, unconfined aquifer only 30 ft thick, to be at high risk of contamination (Clay Commons, Rhode Island Department of Health, written commun., 2004). A well field in the neighboring Village of Pascoag was abandoned in 2001 because of contamination from methyl *tert*-butyl ether (MTBE), thereby requiring Pascoag to connect to the Harrisville water supply. This action more than doubled the population served and caused the water system to operate near capacity. In addition, a second well field in Harrisville has had water-quality concerns (Clay Commons, Rhode Island Department of Health, written commun., 2004). This second well field is in a flood plain near the confluence of two rivers and is susceptible to flooding. In October 2005, flooding due to a major precipitation event required the town to discontinue operations at the well field for nine days; the Central Street well field was then the sole source of water supply.

The Town of Richmond well field in southwestern Rhode Island (fig. 1) was originally installed to provide water to a nearby village where residential wells had been contaminated. Population growth and development are expected to increase in the future in the surrounding area.

The production well fields in Harrisville (Central Street) and Richmond are near surface-water sources in glacial valley-fill settings, but these settings differ. These differences include aquifer thickness and width, the size of the area upgradient of the well field, and the size of the nearby stream. As part of the effort to protect the quality of the ground-water supplies in Rhode Island, the U.S. Geological Survey (USGS), in cooperation with the RIDOH, began a 2-year study in 2004 to increase understanding of the geohydrology and of the important hydrologic factors required to properly delineate areas contributing recharge and the sources of water to the well fields in these contrasting glacial valley-fill settings.

## Purpose and Scope

This report describes the geohydrology and the areas contributing recharge and sources of water to the Village of Harrisville production well field (Central Street), which is composed of three wells, and to the Town of Richmond production well field, which is composed of two wells. Numerical ground-water-flow models were developed and calibrated for each study site on the basis of geologic and hydrologic data collected during this and previous investigations. The simulated areas contributing recharge to the production wells and the associated simulated ground-water traveltimes from recharging locations to withdrawal points in these two glacial valley-fill settings are shown on maps for selected pumping rates and average, steady-state hydrologic conditions. Maps also show the effects of selected hydrologic properties and of recharge rates on the sizes, shapes, and locations of the delineated areas contributing recharge and on the sources of water to the production wells.

## Description of Study Sites and Previous Investigations

The Harrisville study site is in the Clear River watershed in northwestern Rhode Island and the Richmond study site is in the Wood River watershed in southwestern Rhode Island (fig. 1). The climate is humid and temperate with an average annual temperature of about 50°F and average annual precipitation of 49 in. over the northern and 51 in. over the

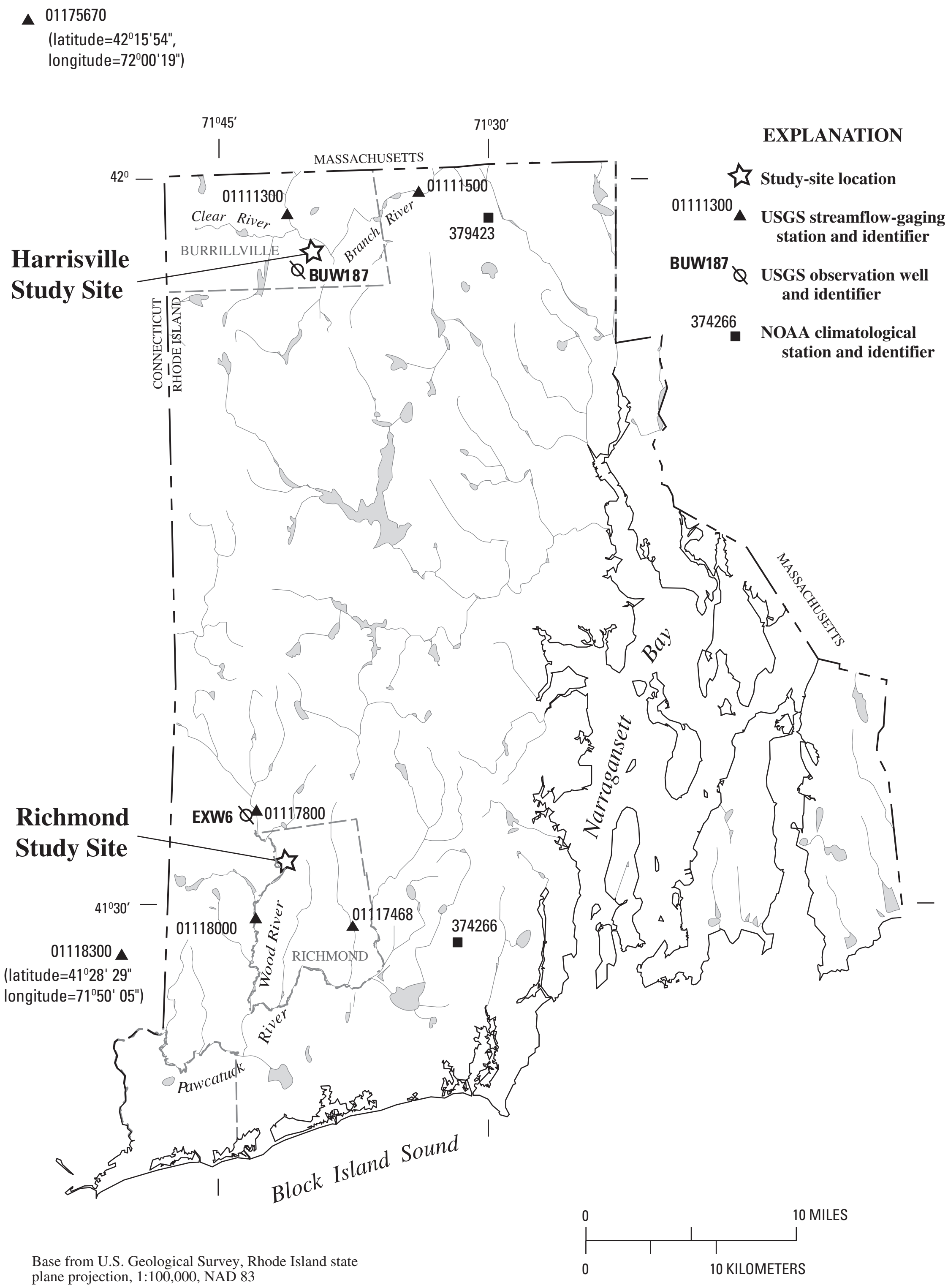



**Figure 1.** Study sites in Rhode Island and selected U.S. Geological Survey (USGS) long-term network streamflow-gaging stations and observation wells, and National Oceanic and Atmospheric Administration (NOAA) climatological stations.

southern parts of the state on the basis of records from 1960 through 2005 for the Woonsocket (379423) and Kingston (374266), Rhode Island, climatological stations (National Oceanic and Atmospheric Administration, 2006) (fig. 1).

Ground water at the study sites is stored and transmitted in surficial sediments of glacial origin—till and stratified deposits—and in the underlying bedrock. A thin, discontinuous layer of till deposited directly on the bedrock by glacial ice is composed of a poorly sorted mixture of sediments ranging in size from clay to boulders. Stratified deposits overlie the till in the valleys and consist of well-sorted, layered sediments ranging in size from clay to gravel deposited by glacial meltwater. The direction of ground-water flow is generally from the till in the uplands toward streams and stratified deposits in the valleys. The production wells are screened in coarse-grained stratified deposits composed of sand and gravel. Sand and gravel deposits are the primary aquifers in Rhode Island because of the higher storage and transmissive properties of these deposits compared to other geologic units.

The Harrisville study site is characterized by narrow river valleys approximately 0.5 mi wide bordered by steep hillslopes. The well field, which is in close proximity to a brook in a small watershed of the Clear River, is screened in thin and shallow saturated stratified sediments. Geologic and hydrologic information was available from regional USGS investigations of areas that include the study site. Previous studies of areas of the Clear River watershed (Hahn, 1961) and the Branch River watershed in Rhode Island (Johnston and Dickerman, 1974a) analyzed the ground-water and surface-water resources. Site-specific information from these regional investigations was available for the older production wells at the study site. A reconnaissance study of ground-water conditions in the area covered by the USGS Chepachet quadrangle, which includes the study site, was completed by Hahn and Hansen (1961). This study published a general map of the surficial geology with the approximate location of the contact between the stratified deposits and till; detailed mapping of the surficial deposits has not been completed for the area within the Chepachet quadrangle.

The Richmond study site is characterized by a moderately broad river valley approximately 1.2 mi wide bordered by till-covered uplands. The well field is near the Wood River, a large tributary to the Pawcatuck River, and is screened deeper and in thicker saturated sediments than the well field at the Harrisville study site. Previous USGS investigations in the area covered by the USGS Hope Valley quadrangle, which includes the study site, include a reconnaissance of the ground-water conditions (Bierschenk and Hahn, 1959) and detailed mapping of the surficial deposits (Feininger, 1962). The first comprehensive investigation of the ground-water and surface-water resources of the lower Pawcatuck River watershed, which includes the Wood River watershed, was done by Gonthier and others (1974). More recently, a study on the availability of ground water in the upper Wood River watershed by Dickerman and Bell (1993) included a simplified two-dimensional flow model of the valley-fill deposits. An associated data report (Dickerman and others, 1989) compiled geologic and hydrologic data, including data from the previous studies.

# Numerical Modeling

Many hydrologic features and processes may affect the size, shape, and location of the area contributing recharge to a well; this area is defined as the surface area where water recharges the ground water and then flows toward and discharges to the well (Reilly and Pollock, 1993). Features and processes such as ground-water systems with irregular geometry and complex lithology, or the interaction between individual pumping wells and hydrologic features such as surface-water bodies, are difficult to represent with analytical methods. Three-dimensional finite-difference numerical ground-water-flow models, however, can represent these and other geologic and hydrologic features and processes. Information provided by a numerical model on the source of water to a well can also be useful in the protection of public health in Rhode Island.

Ground-water-flow models based on the computer code MODFLOW-2000 (McDonald and Harbaugh, 1988; Harbaugh and others, 2000) and capable of simulating the response of the ground-water system to production-well withdrawals were developed for each of the two study sites. Areas contributing recharge and the sources of water to the production wells were determined on the basis of model simulations of average, steady-state hydrologic conditions and by use of the particle-tracking program MODPATH (Pollock, 1994). The particle-tracking program calculates ground-water-flow paths and traveltimes on the basis of the head distribution computed by the ground-water-flow simulation. Areas contributing recharge were delineated by forward tracking of particles from the top faces of model cells in recharging areas to the discharging wells. Particles were allowed to pass through model cells with weak sinks, which remove only a part of the water that flows into the cell.

Development of a ground-water-flow model required that the geometry and hydraulic properties of the ground-water system and fluxes into and out of the model be quantified. Model-input parameters were assigned from the literature or calibrated to water levels and streamflows. Models were calibrated by adjusting model-input parameters within reasonable ranges until the simulated water levels and streamflows approximated measured water levels and streamflows. Improvements in model-simulation results were achieved by minimizing the differences, or residuals, between simulated and measured values. Models, however, produce non unique solutions such that the same simulated response in water levels and streamflows may be obtained by using different combinations of hydraulic properties and recharge rates. This nonuniqueness was addressed by a sensitivity and uncertainty analysis for each study-site model to demonstrate how alternative but plausible model-input values affect the simulated areas contributing recharge to the well fields.

## Hydraulic Properties

The hydraulic properties of glacial till are not well known. Aquifer tests and laboratory measurements indicated that hydraulic conductivity values for till in southern Rhode Island range from 0.07 to 41 ft/d with a median of 0.7 ft/d (Allen and others, 1966). Melvin and others (1992) summarized the hydraulic properties of till from previous studies in southern New England: for till derived from crystalline bedrock, horizontal hydraulic conductivities ranged from 0.004 to 65 ft/d and vertical hydraulic conductivities ranged from 0.013 to 96 ft/d. Porosity values determined from a limited number of measurements in southern Rhode Island by Allen and others (1963) ranged from 0.23 to 0.50 and averaged 0.30. Porosity values ranged from 0.22 to 0.41 and averaged 0.33 from a limited number of measurements in southern New England (Melvin and others, 1992).

Horizontal hydraulic conductivity values of glacial stratified deposits were estimated from lithology and available aquifer-test results at the production-well fields. Values determined from lithology were based on the relation between horizontal hydraulic conductivity and grain size determined by Rosenshein and others (1968) from aquifer-test results in southern Rhode Island. These values are 50 ft/d for fine sand, 100 ft/d for sand, 200 ft/d for sand and gravel, and 500 ft/d for gravel. The vertical hydraulic conductivity averaged one-tenth the horizontal hydraulic conductivity on the basis of aquifer-test analyses in southern Rhode Island by Dickerman (1984). The porosities of 24 stratified-sediment samples in southern Rhode Island reported by Allen and others (1963) ranged from 0.26 to 0.42 with an average value of 0.34. LeBlanc (1987) reported a range of porosities from 0.35 to 0.40 for stratified deposits on western Cape Cod, Massachusetts.

Hydraulic properties of crystalline bedrock are generally low. Analysis of specific-capacity data from bedrock wells in eastern Connecticut indicated an average hydraulic conductivity of 0.5 ft/d (Randall and others, 1966). Lower values of 0.02 and 0.09 ft/d for crystalline bedrock in northern New Hampshire were determined through model calibration (Tiedeman and others, 1997). The range of porosity values for crystalline rock summarized in Meinzer (1923) range from 0.0002 to 0.02.

The interaction between surface water and ground water requires a conductance term that incorporates the geometry and the vertical hydraulic conductivity of the bed sediments of the surface-water body. Reported vertical hydraulic conductivity values ranged from 0.1 to 17 ft/d for bed sediments in Rhode Island (Roshenshein and others, 1968; Gonthier and others, 1974; Johnston and Dickerman, 1974b) and Massachusetts (Lapham, 1989; de Lima, 1991; Friesz, 1996; Friesz and Church, 2001). The vertical hydraulic conductivity of coarse-grained sediments in these studies typically ranged from 1 to 3 ft/d and from 0.1 to 0.7 ft/d for fine-grained sediments.

## Recharge Rates

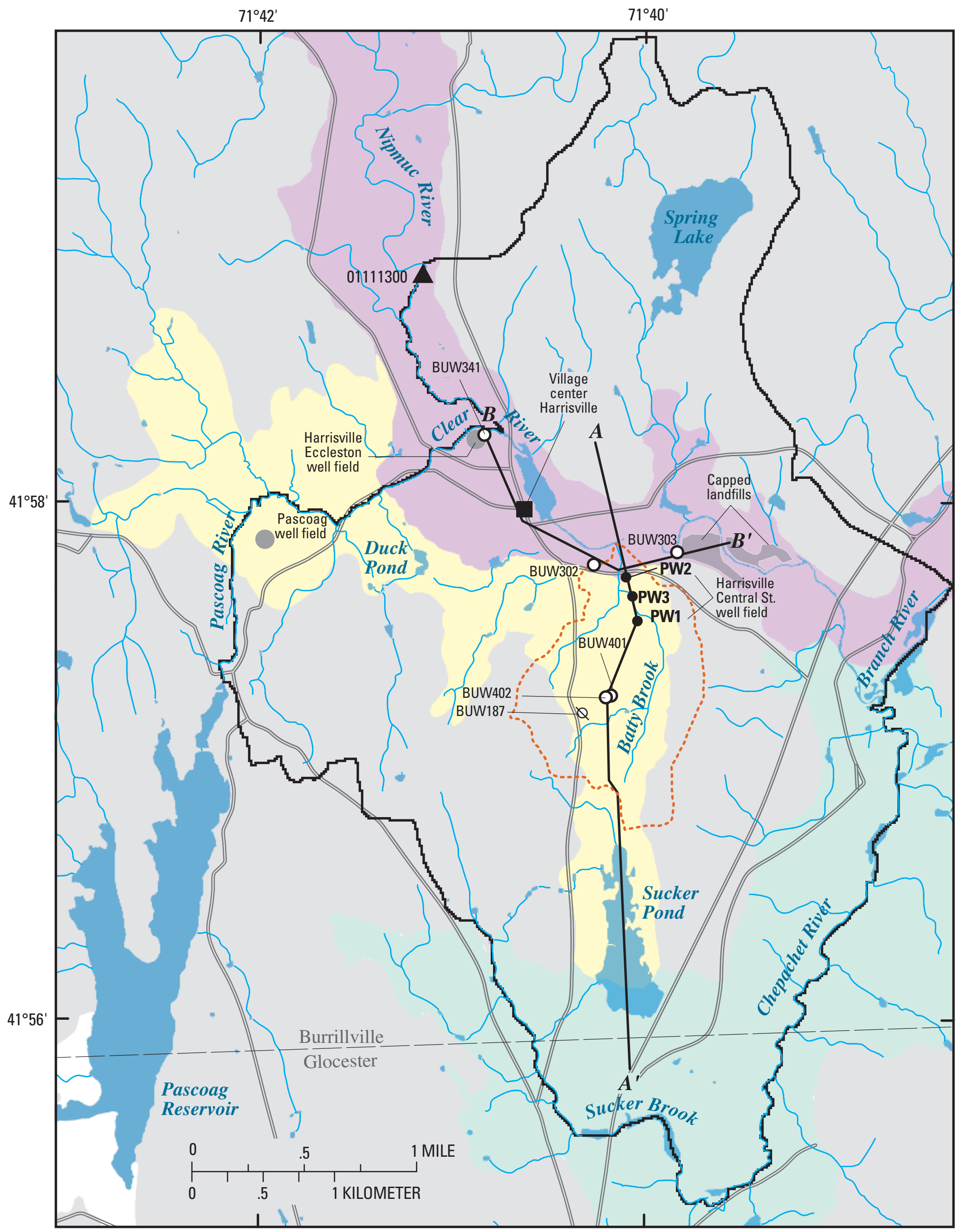
Recharge in upland areas is primarily from direct infiltration of precipitation but may also include leakage from streams, ponds, and wetlands. Recharge rates in upland settings are not well understood and conceptually are highly variable, ranging from near zero in low-permeability tills on steep topography where the water table is near the land surface to values approaching mean annual runoff (precipitation minus evapotranspiration) in sandy tills on moderate slopes where the water table is perennially below the land surface.

The application of a mathematical relation derived from Connecticut streamflow records and geology indicated that ground-water discharge, a measure of effective recharge (ground-water recharge minus ground-water evapotranspiration), is about 35 percent of mean annual runoff for till areas (Mazzaferro and others, 1979). Computerized hydrograph-separation techniques for long-term streamflow records from western Massachusetts and southeastern Rhode Island for watersheds covered predominantly by till (90 percent or greater) indicated effective recharge rates ranging from 16–24 in/yr when mean annual runoff ranged from 27–31 in/yr (Bent, 1995, 1999). For this study, effective recharge also determined by a computerized hydrograph-separation technique for streamflow draining a predominately till watershed in southeastern Connecticut near the Richmond study site fell within this range.

Sources of recharge to valley-fill aquifers include direct infiltration of precipitation, runoff from adjacent upland hillslopes, and natural infiltration from streams that cross a valley from upland areas. In some cases, pumping by wells may also induce water from surface-water bodies. Conceptually, overland runoff is minimal in areas of stratified deposits, and recharge rates from direct infiltration of precipitation should approximate mean annual runoff rates (Lyford and Cohen, 1988). Runoff from adjacent upland hillslopes, either by ground water or surface water, can be a major source of recharge in a valley-fill setting depending on the size of the valley in comparison to the size of the upland area.

# Harrisville Study Site

The Village of Harrisville production well field (Central Street) is in Batty Brook watershed, a small subbasin of the Clear River in the Town of Burrillville, northwestern Rhode Island (figs. 1 and 2). The well field consists of three production wells; the third well became active during this study in October 2004. The study area is characterized by narrow valleys approximately 0.5 mi wide bordered by steep hillslopes. The study area extends to features that serve as hydrologic boundaries in the numerical model: these features include the rivers and streams in the major valleys and upland topographical divides where surface-water and ground-water divides are most likely coincident. The study area is bordered




Base from U.S. Geological Survey, Rhode Island state plane projection, 1:24,000, NAD 83

**EXPLANATION**

- Till and bedrock outcrops
- Model boundary
- Boundary of Batty Brook watershed
- *A* — *A'* Line of geologic cross section
- PW1 — Production well and identifier
- 01111300 — Nipmuc River streamflow-gaging station
- BUW187 — Long-term network observation well and identifier
- BUW402 — Boring and identifier

**Stratified deposits**—Subdivided into depositional environments
- Glacial Lake Chepachet
- Sucker Pond-Batty Brook ice-dammed pond deposits
- Clear River-Nipmuc River deposits
- Undifferentiated

**Figure 2.** Production wells, section lines, selected borings and observation wells, model extent, and surficial geology, Harrisville study site, Rhode Island.

on the west by the Pascoag, Clear, and Nipmuc Rivers, on the south by Sucker Brook, and on the east by the Chepachet and Branch Rivers. The study area is bordered on the southwest and the north by topographical divides. Land uses in and near Batty Brook watershed are primarily forest and rural residential except for a small sand and gravel operation near the well field. The urban center of Harrisville and two capped landfills are about 0.5 mi northwest and northeast, respectively, of the well field.

Characteristics of the three production wells, which are sited 50 to 160 ft from Batty Brook, are listed in table 1. The drilled wells are completed at, or just above, the top of the bedrock surface in a thin but transmissive aquifer consisting of coarse-grained stratified deposits. Well depths range from 31.5 to 36 ft below land surface in about 30 ft of saturated sediments. Areas contributing recharge were determined for both the 2005 average well-field withdrawal rate, 224 gal/min, and the maximum well-field rate, 600 gal/min.

Water levels and streamflows were measured periodically from June 2004 to January 2006 to increase understanding of stream-aquifer interactions at the well-field site. The data-collection network included streambed piezometers, existing observation wells, and temporary streamflow-gaging stations (fig. 3). Seven streambed piezometers consisting of 0.5-ft-long screens were driven to shallow depths beneath the stream. Streamflow-gaging stations, two upstream and one downstream of the well-field site, consisted of 90-degree v-notch weirs with continuous recorders; the weirs were able to capture most of the streamflow except during high flows and the downstream weir was affected by surface runoff from a road and parking lot. In addition to surface-water levels measured at the streambed-piezometer locations, a survey of surface-water altitudes in May and June 2005 was made at streams in Batty Brook watershed, at the Clear River at the confluence with Batty Brook (fig. 3), and at Sucker Pond. Lithologic logs and seismic-refraction surveys from local and state agencies and from USGS reports and files were compiled to define the bedrock surface and the grain size of stratified deposits.

## Geology

The Harrisville study area is characterized by till-covered bedrock uplands cut by valleys that contain glacial-meltwater deposits of variable thicknesses (fig. 2). Postglacial sediments overlie glacial deposits in flood-plain and wetland areas. Bedrock beneath the study area consists predominately of late Proterozoic plutonic granite-gneiss rock units, with local more mafic intrusions, and layered gneissic and schistose rock units of the Blackstone Group and Absalona Formation (Quinn, 1967). All of these rock units are part of the Avalon terrane (Hermes and others, 1994). Bedrock valleys partially filled with glacial meltwater sediments include the valley of the east-flowing Clear River and several north-draining tributary valleys, the largest of which contains the Chepachet River. The altitude of the bedrock surface beneath these valleys within

**Table 1.** Characteristics of the production wells for the Harrisville and Richmond study sites, Rhode Island.

[Altitudes in feet relative to NGVD 29; USGS, U.S. Geological Survey; ft, foot; in., inch; gal/min, gallons per minute]

| Name | | Year drilled | Altitude of land surface (ft) | Screen diameter (in.) | Depth of screen top and bottom below land surface (ft) | Screen altitude top and bottom (ft) | Distance to stream (ft) | Average pumping rate (gal/min) | Maximum pumping rate (gal/min) |
|---|---|---|---|---|---|---|---|---|---|
| USGS | Local | | | | | | | | |
| Harrisville (Central Street) | | | | | | | | | |
| BUW149 | PW2 | 1958 | 325.9 | 12 | 21.5–32 | 304.4–293.9 | 50 | [1]73 | [2]200 |
| BUW359 | PW3 | 1968 | 331.6 | 18 | 25.5–36 | 306.1–295.6 | 110 | [1]73 | [2]200 |
| BUW400 | PW1 | 2003 | 341.0 | 18 | 26.5–31.5 | 314.5–309.5 | 160 | [1]78 | [3]200 |
| Total | | | | | | | | 224 | 600 |
| Richmond | | | | | | | | | |
| RIW815 | PW1 | 1985 | 111.8 | 18 | 49.6–65 | 62.2–46.8 | 360 | [4]39 | [5]450 |
| RIW816 | PW2 | 1995 | 107.4 | 8 | 42–54 | 65.4–53.4 | 580 | Backup | [5]225 |
| Total | | | | | | | | 39 | 675 |

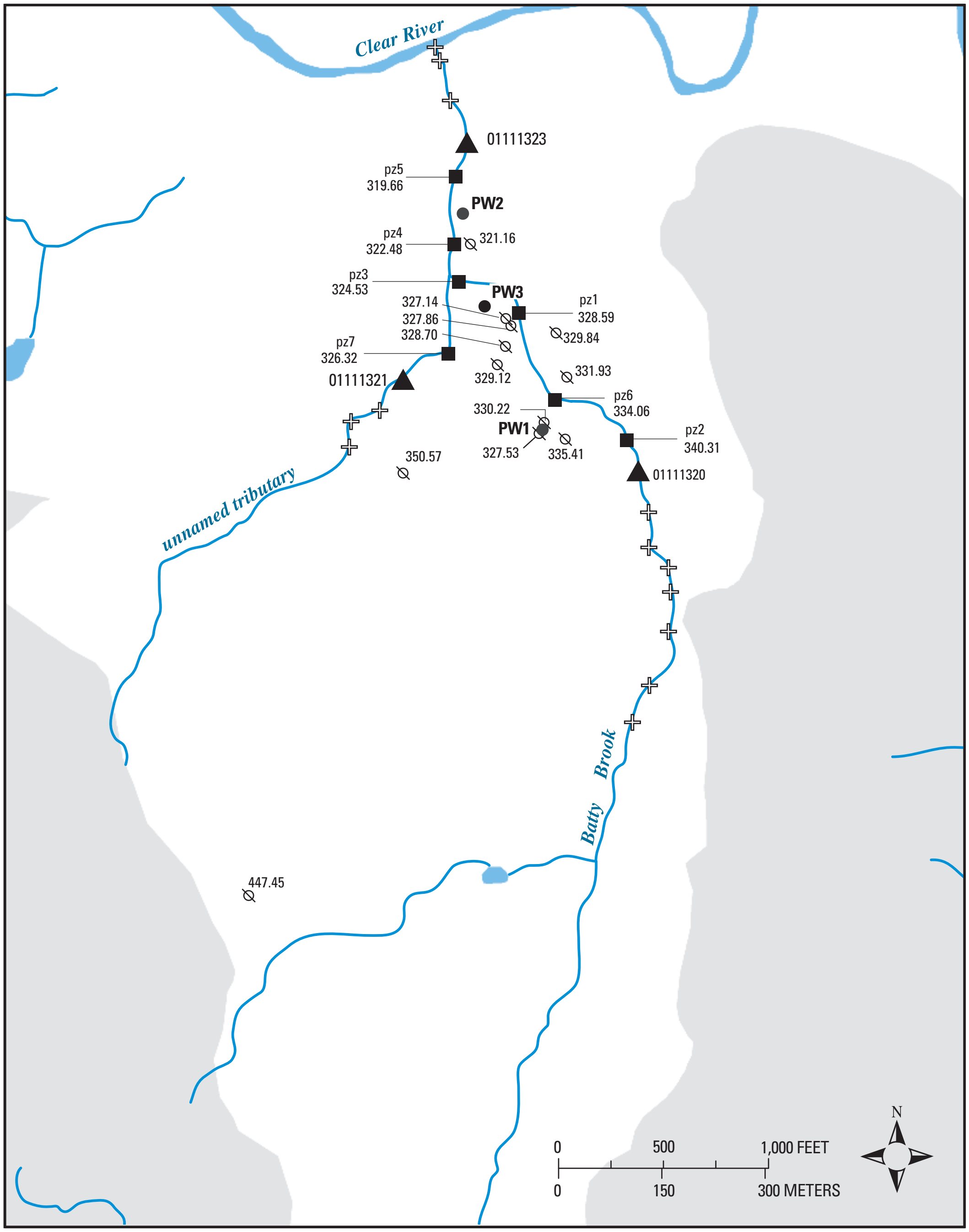
[1] Average for year 2005.

[2] Rate used by Rhode Island Department of Environmental Management to determine contributing area by an analytical method.

[3] Estimated yield from well-completion log.

[4] Average for years 2000–04.

[5] Maximum rated capacity of pump.




Base from U.S. Geological Survey, Rhode Island state plane projection, 1:24,000, NAD 83

EXPLANATION

Stratified deposits

Till and bedrock outcrops

PW1 **Production well and identifier**

Pz2 340.31 **Streambed piezometer and identifier—**Altitude of water level measured on June 24, 2005, in feet above NGVD 29

350.57 **Observation well—**Altitude of water level measured on June 24, 2005, in feet above NGVD 29

01111320 **Temporary streamflow-gaging station and identifier**

**Stream-stage measurement site (in addition to piezometer and station sites)**

**Figure 3.** Data-collection network near production wells and water levels on June 24, 2005, Harrisville study site, Rhode Island.

the study area is shown on figure 4. Bedrock-surface contours were constructed on the basis of locations of bedrock outcrops, knowledge of bedrock structure, interpretation of glacial-till thickness from topography and aerial photographs, and available well data and seismic-refraction surveys.

The general distribution of glacial deposits was compiled from unpublished field maps (E. London, USGS, written commun., 2005) and analysis of aerial photographs. Glacial deposits include subglacially deposited till and stratified glacial-meltwater deposits. Stratified deposits generally were less areally extensive than previously published. Glacial deposits overlie the bedrock surface and range from a few feet to as much as 170 ft thick in parts of the Chepachet River valley. In the Sucker Pond valley south of the well field and in the Clear River valley north of the well field, glacial deposits are generally less than 80–90 ft thick. The distribution of surficial materials between the land surface and the bedrock surface is shown on cross sections A-A´ and B-B´ (fig. 5). The cross sections illustrate the characteristic vertical succession of glacial till, glacial-meltwater deposits (sand and gravel, sand) and postglacial deposits (alluvial). Most of these materials are deposits of the last two continental ice sheets that covered New England during the middle and late Pleistocene. Most were laid down during the advance and retreat of the last (late Wisconsinan) ice sheet, which reached its terminus on Long Island, N.Y., about 21,000 radiocarbon years ago, and was retreating northward through northern Rhode Island between 16,500 and 16,000 radiocarbon years ago (Stone and Borns, 1986; Stone and others, 2005).

Glacial till in the Harrisville study area was deposited directly by glacier ice and is characterized as a nonsorted, nonlayered, relatively compact mixture of sand, silt, and clay with variable amounts of stones and large boulders. Till blankets the bedrock surface in most places and is generally less than 10–15 ft thick. In many places within the area shown as “till and bedrock outcrops” (fig. 2), till is absent and bedrock is at the land surface. Till also commonly underlies glacial stratified deposits in the valleys where it is generally less than 10 ft thick.

Glacial-meltwater deposits that consist predominately of glaciodeltaic gravel, sand and gravel, and sand are in all of the valleys in the study area. Glacial lakes developed in these valleys as the ice-margin retreated through the area; meltwater deposits were laid down at successively lower altitudes, as lower meltwater pathways were uncovered to the north (see discussion of this meltwater depositional process in Stone and others, 2005). Glacial Lake Chepachet occupied the north-draining Chepachet River valley (fig. 2), and successive ice-marginal deltas deposited in this lake were controlled in altitude by a series of spillways over drainage divides to the south and east of the map area. The highest altitudes of deltas in the Sucker Brook and Chepachet River valleys are 505 ft. An ice-marginal delta deposited into glacial Lake Chepachet at the south end of Sucker Pond (see cross section A-A´, fig. 5) reaches an altitude of 495 ft; this altitude was controlled by a 485-ft-high spillway 2.2 mi southeast of Sucker Pond. Lower deltas built into glacial Lake Chepachet were controlled by a 395-ft-high spillway across the eastern drainage divide.

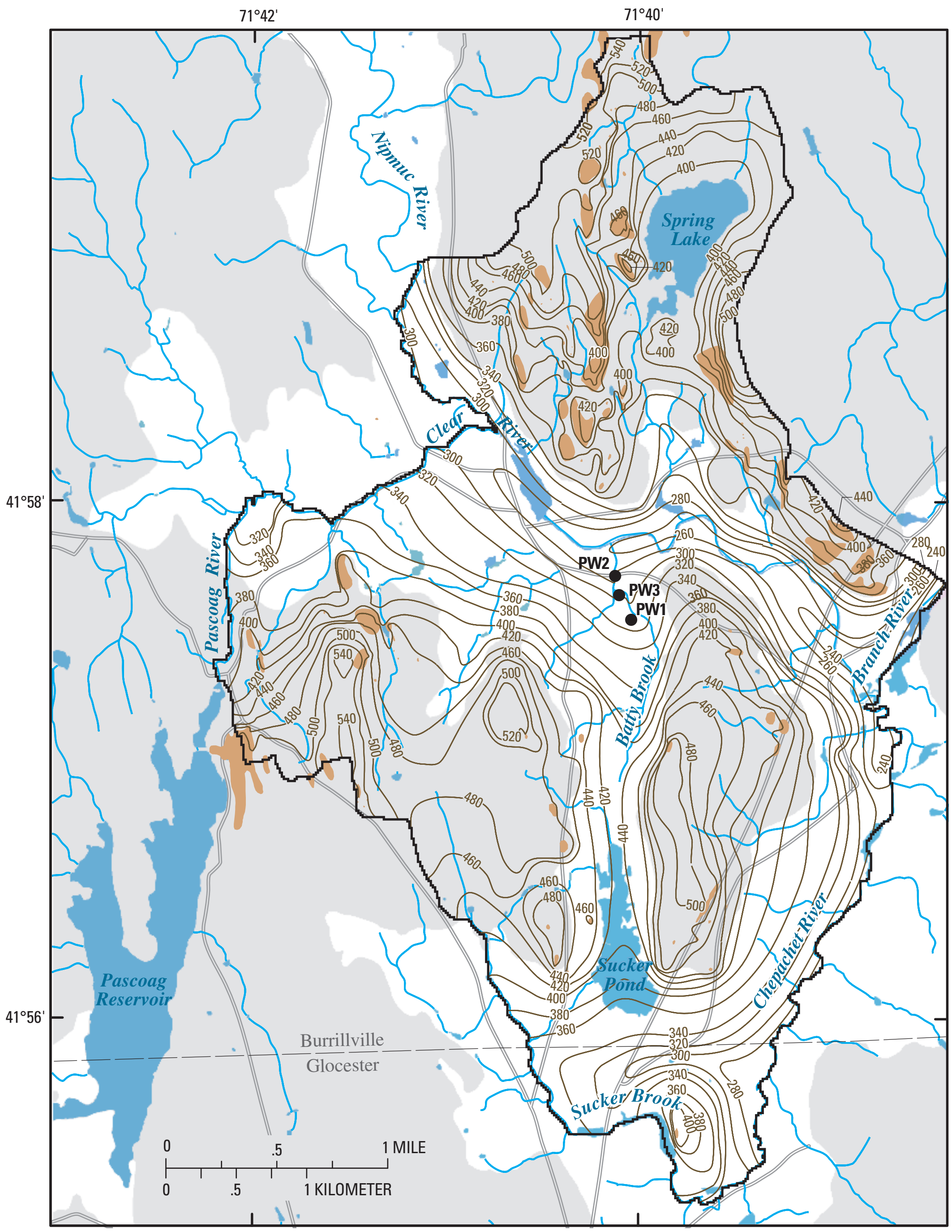
A series of small ice-dammed lakes formed in the Sucker Pond-Batty Brook valley as the ice margin continued to retreat northward (fig. 2). The deltaic-surface altitudes of glacial-meltwater deposits surrounding Sucker Pond reach 475–480 ft and include gravelly ice-channel fillings (or eskers); one of these ridges forms the Sucker Brook-Batty Brook surface-water divide. These sediments were deposited in a small glacial lake dammed behind the 495-ft-high delta; meltwater spilled from this lake through a channel cut through the northeast edge of the delta. To the north in this valley, another delta with a noncollapsed surface altitude of 465 ft was graded to a small, ice-dammed pond controlled by a 465-ft-high spillway across the eastern divide of Batty Brook watershed. The northern ice-proximal part of this deltaic deposit, composed of collapsed, coarse gravel and sand, is tapped by the Harrisville production wells (fig. 5, section A-A´). Deposits banked against the southern hillside of the Clear River valley have noncollapsed delta surfaces at an altitude of 415 ft and were graded to a level of ponding controlled by a 415-ft-high spillway across the eastern divide of Batty Brook watershed north of the earlier one.

Glacial-meltwater deposits in the Clear River valley (fig. 2) were deposited in a series of glacial ponds that developed because of sediment dams downstream and in the Branch River valley. Deltaic deposits in the valley along section line B-B´ (fig. 5) are mostly noncollapsed, have surface altitudes of 345–365 ft, and consist of horizontally bedded gravelly topset beds 5–15 ft in thickness overlying dipping sandy foreset beds as much as 90 ft thick.

Postglacial deposits locally overlie glacial deposits and include flood-plain alluvium along rivers and streams and organic peat and muck (wetland deposits) in low-lying closed depressions. These deposits are not shown on figure 2, but are illustrated on geologic sections (fig. 5).

## Hydrology

The production wells are in Batty Brook watershed, which drains 0.64 mi$^2$ at its confluence with the Clear River (fig. 2). The Clear River flows east and joins the northeast-draining Chepachet River to form the Branch River. The north part of a north-south-trending valley between the Clear and Chepachet River watersheds is drained by Batty Brook, and the south part is drained by Sucker Pond and Sucker Brook, which flows into Chepachet River. Till uplands southwest and southeast of the well-field site also form watershed divides between the Clear and Chepachet River watersheds. The stream network shown in figure 2 is delineated at the 1:5,000 scale. Streams at the 1:24,000 scale did not adequately represent the stream network in the study area; these streams include several small tributaries in and near Batty Brook watershed.




Base from U.S. Geological Survey, Rhode Island state plane projection, 1:24,000, NAD 83

**EXPLANATION**

**Stratified deposits**

**Till**

**Bedrock outcrops in study area**

**Model boundary**

500 **Bedrock-surface altitude**—Contour interval is 20 feet

PW1 **Production well and identifier**

**Figure 4.** Bedrock-surface contours, Harrisville study site, Rhode Island.

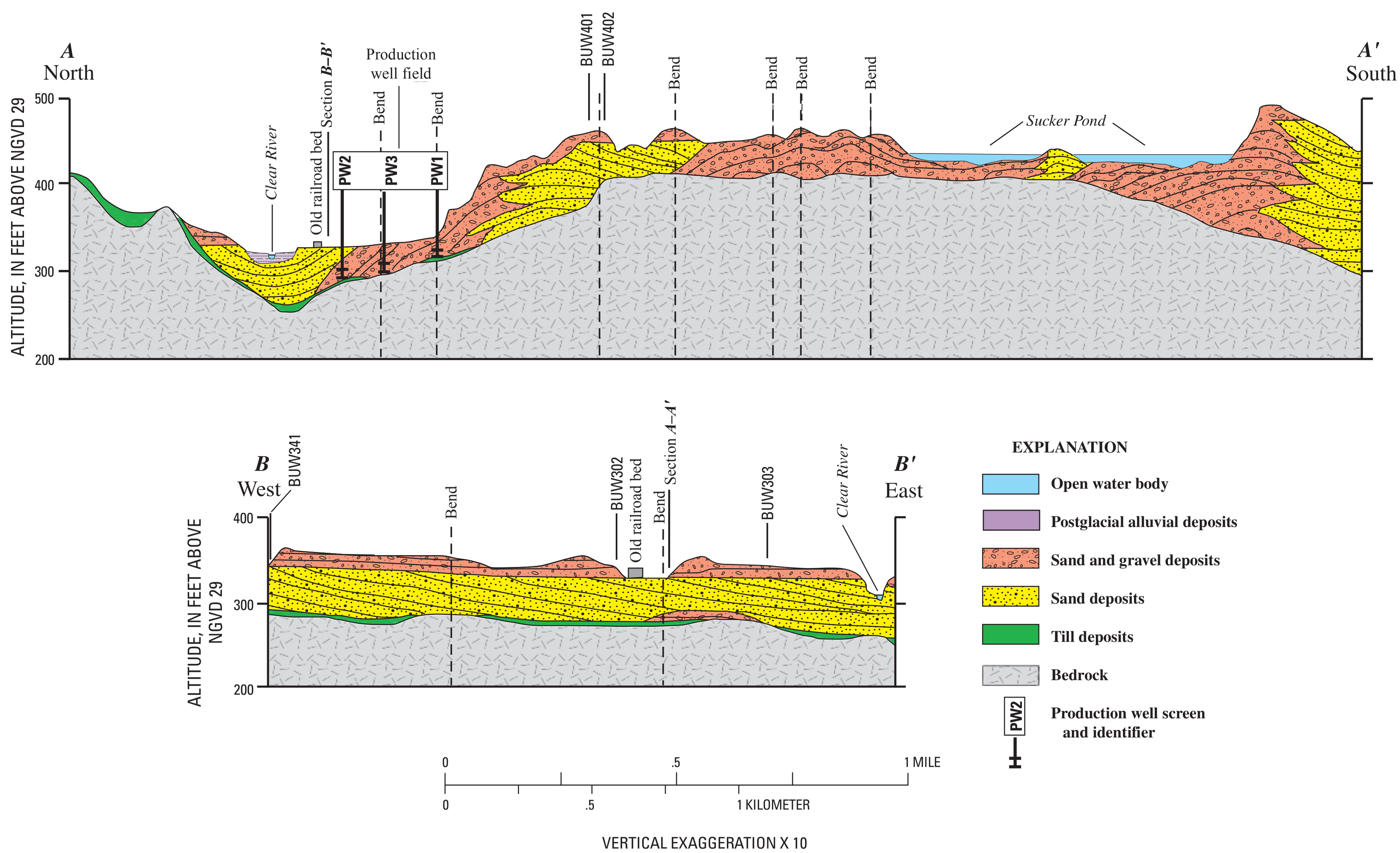



**Figure 5.** Geologic cross sections (lines of sections A-A′ and B-B′ are shown in figure 2), Harrisville study site, Rhode Island.

The production wells are screened in thin but transmissive sand and gravel deposits on opposite sides of Batty Brook (figs. 2 and 5). Distances from the production wells to Batty Brook range from 50 ft for PW2 to 160 ft for PW1. The saturated thicknesses of the stratified deposits in Batty Brook watershed range from about 10 ft in its headwaters to 30 ft at the well-field site to about 50 ft in the valley axis of the Clear River. The average hydraulic conductivities of the stratified deposits determined from lithologic logs at and near each production well range from 210 ft/d at PW2 (Johnston and Dickerman, 1974a) to 140 ft/d at the new PW1. The average hydraulic conductivities calculated at PW3 and PW2 from specific-capacity data (Johnston and Dickerman, 1974a) were higher than hydraulic conductivity estimates from lithologic logs and ranged from 260 to 480 ft/d.

A hydrograph from USGS long-term observation well BUW187 in the upper part of Batty Brook watershed illustrates the seasonal variations in water levels typical of stratified deposits (figs. 3 and 6); also shown in figure 6 is the data-collection period compared to these seasonal fluctuations. Ground-water levels are generally highest in early spring and lowest in the fall. Ground-water level fluctuations are caused by increased recharge rates from late fall to spring when there is little or no evapotranspiration. The ground-water gradient in Batty Brook watershed is steep, even in the stratified deposits. The head difference between water levels at BUW187 and the well field is 118 ft and between the well field and the Clear River is 19 ft; these differences were measured over distances of 2,800 ft and 1,500 ft, respectively.

Streamflow records from two nearby long-term streamflow-gaging stations provided a guide in assigning recharge rates in the study area (fig. 1 and table 2). The drainage area of the Branch River station (01111500) includes the model area and the Nipmuc River station (01111300) is 1.7 mi northwest of the well-field site. Mean annual streamflow (precipitation minus evapotranspiration) is equivalent to about 26 in/yr over the drainage areas. Mean annual ground-water discharge (effective recharge), calculated by use of the hydrograph-separation technique PART (Rutledge, 1998), was about 19 to 20 in/yr or 72 to 76 percent of total streamflow. These rates are an average over the entire watershed, including areas of stratified deposits, till, surface-water bodies, wetlands, and a variety of land uses. The difference between mean annual streamflow and ground-water discharge is surface runoff from areas that reject infiltration of precipitation; these areas include impervious surfaces, surface-water bodies, wetlands, and areas where the water table is at the land surface seasonally, such as some till areas. Batty Brook watershed consists primarily of permeable stratified deposits and adjacent upland hillslopes. A recharge rate of 26 in/yr over the 0.64-mi$^2$ watershed is equivalent to 1.23 ft$^3$/s or 552 gal/min. The 2005 well-field withdrawal rate of 224 gal/min is about 40 percent of the total water available in this small watershed, but the maximum well-field withdrawal rate of 600 gal/min exceeds it; thus, for the steady-state model simulation, the well field must derive part of its pumped water from outside Batty Brook watershed.

Ground water that discharges to streams in Batty Brook watershed is a potential source of water to the well field through streamflow loss, either naturally, induced by pumping of a well, or both. Natural streamflow loss may occur because the increased saturated thickness and hydraulic conductivity of the sand and gravel deposits at the well-field site may cause ground-water levels to be lower than the streambed. Paired water levels at streambed-piezometer sites and streamflows at the streamflow-gaging stations provide insights into stream-aquifer interactions at the well-field site. The production wells, however, were operated on a varied pumping schedule, usually in a combination of two or more, or not at all. Well-field withdrawals were highest during the summer months, a period of generally minimal precipitation recharge.

Ground-water and surface-water levels were measured periodically at seven streambed-piezometer sites (PZ1–PZ7) upstream and downstream of the well field and between the wells (fig. 3); measurements were generally made when two or more of the wells were pumping. Paired measurements of ground-water and surface-water levels indicate the direction of flow between the stream and the underlying sediments (fig. 7); water levels at PZ3 site are typical of the streambed piezometers not shown (PZ1, PZ4, and PZ7). In general, paired water levels indicated that the direction of flow was downward except during periods of high seasonal recharge rates and low pumping rates. Measurements made at PZ2 show the response of water levels to the new production well PW1, which began pumping at the end of October 2004. Before pumping, water levels show a slight downward head gradient except after a precipitation event in late September 2004. Once the new production well began pumping, the downward head gradient increased.

In June 2005, water levels at the streambed-piezometer sites were measured during a period of normal pumping operation, then no pumping, followed by continuous pumping at all three production wells. On June 21, after about 14 hours of no pumping and 26 hours after minimal pumping, either the ground-water levels, except in PZ2, were equivalent to the surface-water levels, or the downward vertical gradients were less compared to the previous measurement made during pumping withdrawals. The succeeding four sets of measurements from June 21–24 at each piezometer during continuous pumping show an increase in the downward vertical gradient. Water levels measured in available observation wells between the production wells and the streambed piezometers after three days of continuous pumping indicate that the direction of ground-water flow was from the stream to the production wells (fig. 3).

A comparison of instantaneous streamflow measurements made in June and July 2004, and of mean daily streamflow from the weirs upstream (01111320 and 01111321) and downstream (01111323) of the well-field site from November 2004 to November 2005, indicated that during June, a month at or near long-term average ground-water levels (fig. 6), a net streamflow loss over the reach began and continued until ground-water levels returned to long-term average levels in

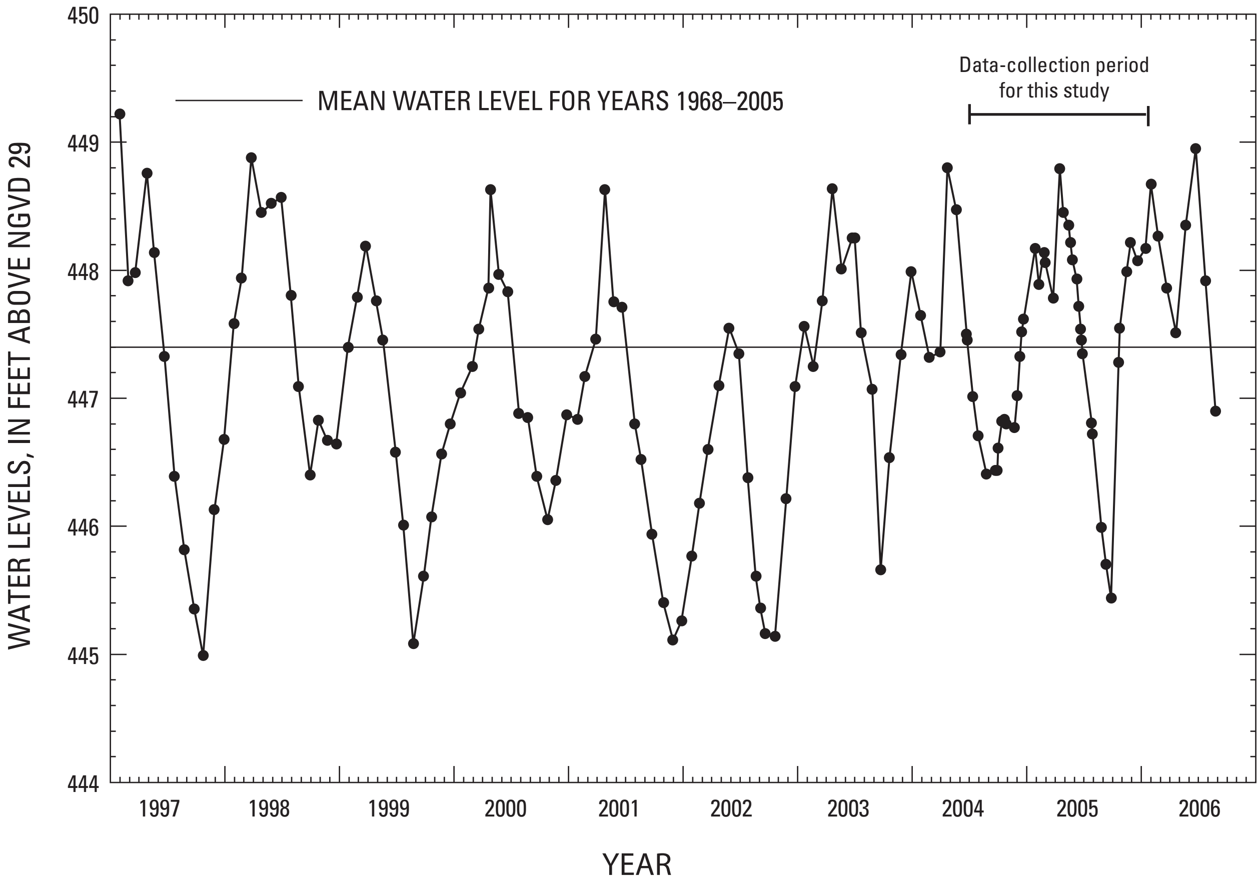



**Figure 6.** Water levels measured in observation well BUW187, 1997–2006 (well location shown in figures 1 and 2), Harrisville study site, Rhode Island.

**Table 2.** Streamflow and drainage-area characteristics of the Branch and Nipmuc River streamflow-gaging stations, Harrisville study site, Rhode Island.

[USGS, U.S. Geological Survey. USGS station number: Locations shown on figures 1 and 2; mi², square mile; ft³/s, cubic feet per second; in/yr, inches per year; PART (Rutledge, 1998) hydrograph-separation method. Ground-water discharge index is mean annual ground-water discharge divided by mean annual streamflow.]

| USGS station number | Station name | Drainage area (mi²) | Area of glacial stratified deposits (percent) | Period of record analyzed | Mean annual stream-flow (ft³/s) | Mean annual stream-flow (in/yr) | Mean annual ground-water discharge PART (ft³/s) | Mean annual ground-water discharge PART (in/yr) | Ground-water-discharge index (percent) |
|---|---|---|---|---|---|---|---|---|---|
| 01111300 | Nipmuc River near Harrisville, R.I. | 16.0 | 28 | 1965–90; 1994–03 | 30.6 | 26.0 | 22.1 | 18.8 | 72 |
| 01111500 | Branch River at Forestdale, R.I. | 91.2 | 30 | 1957–2003 | 177.6 | 26.4 | 135.3 | 20.2 | 76 |

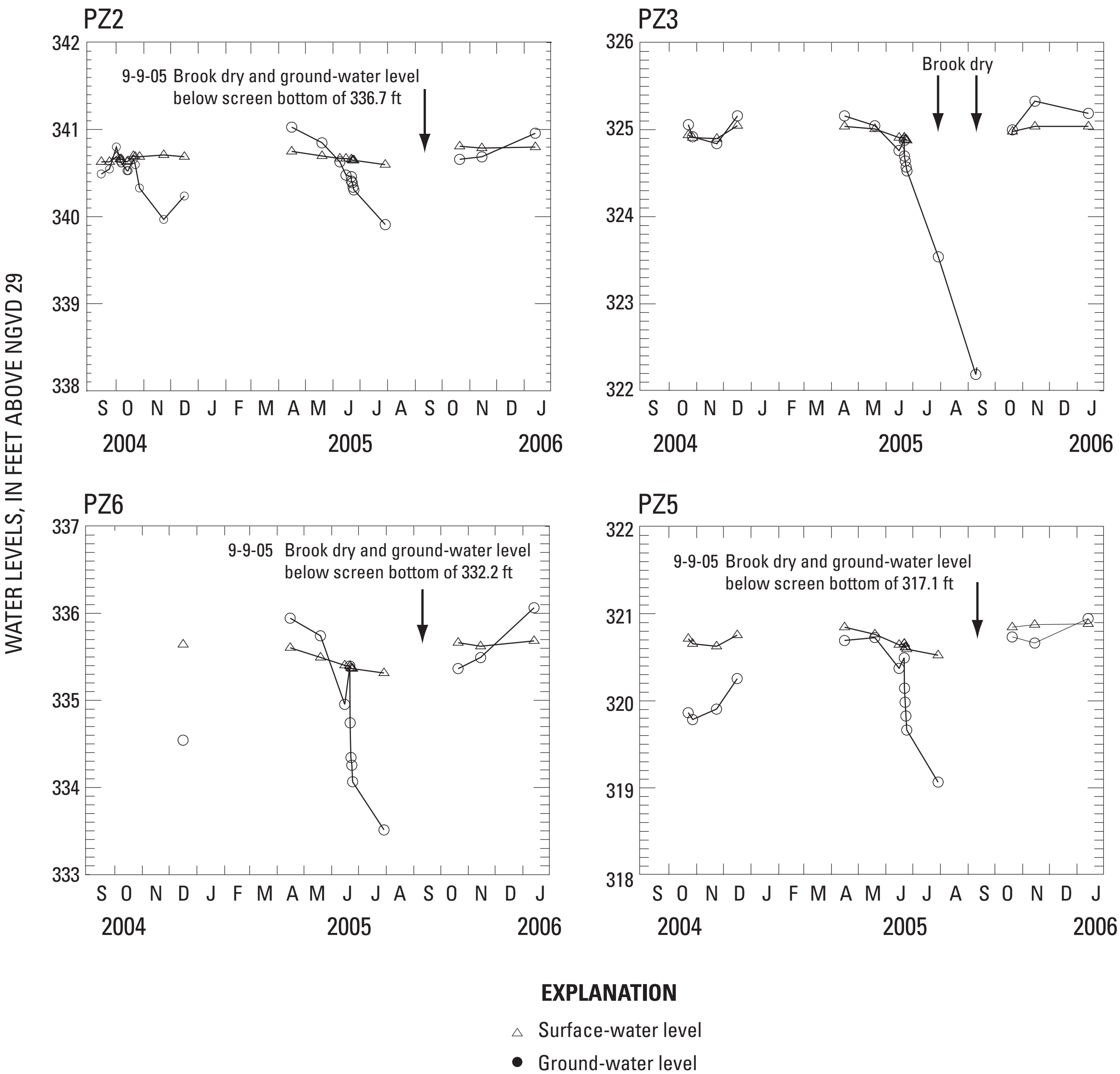



**Figure 7.** Paired surface-water altitudes and ground-water altitudes at selected streambed piezometers in Batty Brook, 2004–2006 (piezometer locations shown in figure 3), Harrisville study site, Rhode Island.

the fall after major precipitation events. The stream reach between stations returned to a net gaining stream in December 2004, after major precipitation events in late November, early December, and October 2005, during which 16 in. of precipitation fell.

Field observations on two dates and streamflow at the weirs indicated that Batty Brook and the unnamed tributary are intermittent streams under the climatic and pumping conditions of 2005. Water levels at observation well BUW187 during the summer were about 0.5 ft below long-term monthly means for the years 1968–2005. On July 29, 2005, streamflow in Batty Brook was completely lost to the stratified deposits between PW1 and PW3, but flow in the unnamed tributary flowed to its confluence with Batty Brook, past the downstream weir, and then intermittently thereafter to the Clear River. On September 9, 2005, flow in Batty Brook ceased about 350 ft upstream of the weir upstream of the well-field site, and flow in the unnamed tributary was completely lost about 20 ft downstream of PZ7. Unpublished field notes from a previous USGS study (Johnston and Dickerman, 1974a) also indicated intermittent-flow conditions in October 1968, when long-term monthly mean ground-water levels were 1.5 ft below average. At that time, PW2 and a former production well on the opposite side of Batty Brook from PW2 were the only two production wells at the site.

Net mean daily streamflow loss between gaging stations was generally 0.05 to 0.1 $ft^3/s$ (22 to 45 gal/min) from June to fall. If all streamflow lost to the stratified deposits between gaging stations is withdrawn by the well field, then streamflow loss is equivalent to 10 to 20 percent of the 2005 average pumping rate. Streamflow loss was greatest for several days after precipitation events caused the intermittent stream to flow continuously and ground-water levels were at their lowest; loss during these conditions was about 30 percent of the 2005 average rate.

Long-term average streamflow at the streamflow-gaging stations upgradient of the well field was estimated for a steady-state, nonpumping model calibration. Streamflows at the upgradient stations may be affected by pumping, but the affected flow is most likely within the uncertainty of the long-term average streamflow estimate. Mean daily streamflows greater than zero from November 1, 2004 to September 30, 2005 at the upgradient weirs were related to concurrent mean daily streamflows at several nearby unregulated long-term streamflow-gaging stations in northern Rhode Island and central Massachusetts. Plots of log-transformed data were made to determine the quality and linearity of the relation. The Maintenance of Variance Extension, Type 1 (MOVE.1) technique developed by Hirsch (1982) was used to provide an equation that relates streamflow at the weirs to that at the long-term stations. The streamflow for only one long-term streamflow-gaging station correlated reasonably well with the streamflows measured at each weir most likely because long-term stations have drainage areas more than an order of magnitude larger than drainage areas of the weirs. Mean annual streamflow computed at the long-term station for complete years of record was entered into the equation to estimate the long-term mean annual streamflow at the weir. Estimated long-term average streamflows were 0.54 $ft^3/s$ for the Batty Brook site and 0.18 $ft^3/s$ for the unnamed tributary site. A detailed description of the MOVE.1 technique for streamflow analysis is described in Ries and Friesz (2000). Information concerning the analysis for each weir is summarized in table 3.

At the maximum pumping rate, the Clear River is also a potential source of water to the well field. The production wells closest to the river, PW2 and PW3, are screened below the river altitude of 310.7 ft surveyed on May 19, 2005 (table 1 and fig. 5). The quantity of river water available for infiltration for average annual conditions far exceeds the combined maximum pumping rates of the study-site well field (600 gal/min) and of the Harrisville Eccleston well field (400 gal/min; Dufresne-Henry, Inc., 2001) at the confluence of the Clear and Nipmuc Rivers (fig. 2). Mean annual streamflow and mean annual ground-water discharge (base flow) for the 42.3-$mi^2$ drainage area of the Clear River upstream of its confluence with Batty Brook are estimated to be 81 and 59 $ft^3/s$, respectively, on the basis of streamflow characteristics at the Nipmuc River station. The combined pumping rate for the two well fields (2.23 $ft^3/s$) is 2.7 percent of mean annual streamflow and 3.8 percent of mean annual ground-water discharge.

## Ground-Water-Flow Model

The ground-water-flow model for the Harrisville study site was designed to simulate long-term, steady-state ground-water levels, flow paths, and traveltimes. The model was calibrated to nonpumping conditions based on historical data and data collected during this study. A general calibration was first done for the model area, and then a detailed calibration was completed for Batty Brook watershed and adjacent areas. A small net increase in streamflow was assumed between the upgradient weirs and the Clear River during nonpumping conditions; the simulated area contributing recharge to the well field was nearly identical for either a small net streamflow gain or loss for nonpumping conditions. Model characteristics, including hydraulic properties and recharge rates, are summarized in table 4.

### Model Design

Ground-water flow in the surficial deposits and the underlying bedrock was simulated by a two-layer numerical model with a uniformly spaced grid. The ground-water-flow model was calibrated to 53 ground-water altitudes and 2 long-term average streamflows in the stratified deposits and to a generally shallow water table that approximates the land-surface configuration in the till uplands. Ground-water levels in the uplands indicate a shallow water table ranging from 1 to 20 ft and averaging 6 ft below land surface in the USGS Chepachet quadrangle (Hahn and Hansen, 1961).

**Table 3.** Summary of the long-term mean annual streamflow analysis for the temporary streamflow-gaging stations upstream of the well-field site, Harrisville study site, Rhode Island.

[USGS, U.S. Geological Survey. USGS station number: Locations shown in figures 1 and 3; mi², square mile; ft³/s, cubic feet per second]

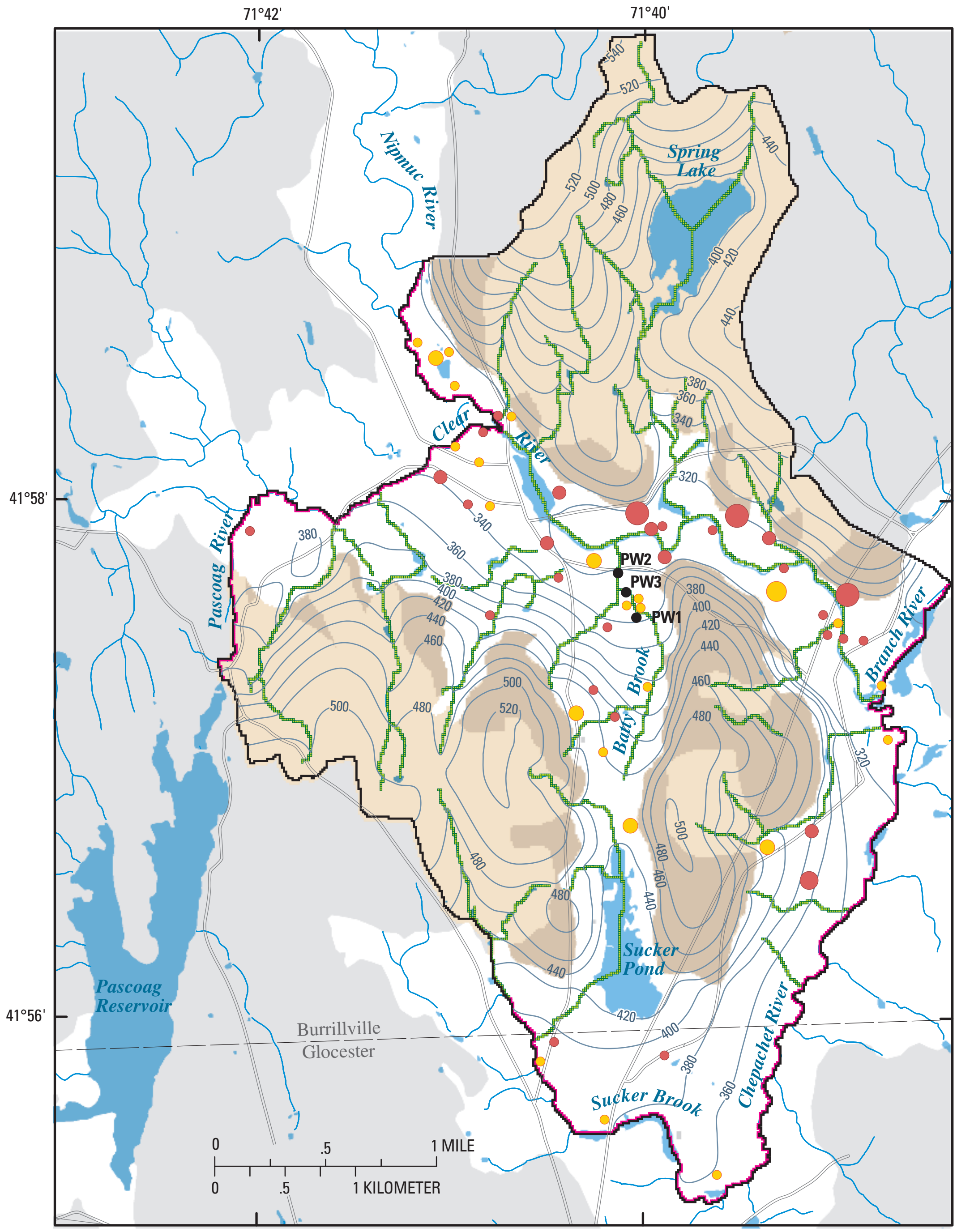
| USGS station number | Station name | Drainage area (mi²) | Number of daily mean streamflows used in relation | Estimated long-term mean annual streamflow (ft³/s) | Streamflow-gaging station used in relation | | Correlation coefficient |
|---|---|---|---|---|---|---|---|
| | | | | | USGS station number | Station name | |
| 01111320 | Batty Brook, upstream of Central Street, at Harrisville, R.I. | 0.34 | 314 | 0.54 | 01111300 | Nipmuc River near Harrisville, R.I. | 0.89 |
| 01111321 | Unnamed Tributary to Batty Brook at Harrisville, R.I. | .14 | 334 | .18 | 01175670 | Sevenmile River near Spencer, Mass. | .74 |

**Table 4.** Summary of simulated values for hydraulic properties and recharge rates in the ground-water-flow model for the Harrisville study site, Rhode Island.

| Characteristics | Simulated values |
|---|---|
| Hydraulic conductivity (feet per day) | |
| Stratified deposits | Sand and gravel at well field: 140 |
| | Remaining sediments: 10–80 |
| Till | Generally 3–4, ranged from 1–5 |
| Bedrock | .05 |
| Ponds and lakes | 1,000–5,000 |
| Ratio of horizontal to vertical hydraulic conductivity | |
| Stratified deposits | 10:1 |
| Till | 10:1 |
| Bedrock | 1:1 |
| Streambed vertical hydraulic conductivity (feet per day) | |
| Coarse-grained deposits | 1 |
| Fine-grained deposits | .1 |
| Porosity | |
| Stratified deposits | 0.35 |
| Till | .35 |
| Bedrock | .02 |
| Recharge rates (inches per year) | |
| Stratified deposits | 26 |
| Upland hillslopes | 26 |
| Upland watersheds | 16 |

Several available sets of ground-water levels were used to calibrate the model in the stratified deposits (fig. 8); these water levels were assumed to be unaffected or minimally affected by pumping wells. In Batty Brook watershed, measurements of four ground-water levels made on April 6, 1985, by GZA GeoEnvironmental, Inc., (1985) and of five ground-water levels made on June 21, 2005, for this study are at or near long-term average annual conditions for USGS long-term observation well BUW187 and the Branch and Nipmuc River streamflow-gaging stations. During April, water levels would normally be at above-average conditions, but because of below-average precipitation in the months preceding April 1985, water levels in observation well BUW187 were at average conditions. The April water levels are in the upper part of Batty Brook watershed. The 2005 water levels, four from observation wells near the well field and one from BUW187, were made about 14 hours after all the production wells stopped pumping and 26 hours after minimal pumping. The four observation wells near the well field were the farthest from the production wells that were available at the site. Water levels, which were measured during different pumping cycles in these four observation wells, indicated that water levels were unaffected or minimally affected by pumping. In addition, stage measurements made at the streambed piezometers and the weirs on June 21, 2005, were used to represent stream altitudes at the well site.

In the remaining area of the model, 44 ground-water levels reported in previous USGS investigations (Hahn and Hansen, 1961; Johnston and Dickerman, 1974a) and at two contamination sites (Rhode Island Department of Environmental Management, 1995; Sage Environmental, 2001) were used in model calibration. Most of these




Base from U.S. Geological Survey, Rhode Island state plane projection, 1:24,000, NAD 83

**EXPLANATION**

**Stratified deposits**

**Till and bedrock outcrops**

**River cell**

**Stream cell**

**Model boundary**

520 **Simulated water-table contour**—Interval is 20 feet

PW1 **Production well and identifier**

**Recharge rates, in inches per year**

- 26 (stratified deposits)
- 26 (upland hillslopes)
- 16 (upland watersheds)

**Residuals, in feet**

Simulated heads greater than measured

- -15 to -10
- -10 to -5
- -5 to 0

Simulated heads less than measured

- 0 to 5
- 5 to 10
- 10 to 15
- 15 to 20

**Figure 8.** Model-boundary types, recharge rates, simulated water-table contours for nonpumping, steady-state conditions, and spatial distribution of residuals (measured-simulated), Harrisville study site, Rhode Island.

water-level measurements were made from 1960 through 1968 in the late spring and fall when hydrologic conditions are normally near average between seasonally high, early-spring water levels and low, late-summer water levels; however, the 1960–1968 water levels still represent a wide range of conditions. Unlike the water levels in Batty Brook watershed, the measuring-point altitude was based on land-surface altitude determined from the USGS Chepachet quadrangle. These altitudes are generally accurate within approximately ±5 ft, but may be less accurate in areas of steep topography.

The two long-term average streamflows calculated at the streamflow-gaging stations upgradient of the well-field site were also used in model calibration. Streamflow at these two sites may have been affected by pumping withdrawals, but the affected flow is most likely within the uncertainty of the long-term average.

The ground-water-flow model extended to natural hydrologic boundaries beyond the likely area contributing recharge to the well field (fig. 8). This extent also minimized the effects of boundaries on simulated heads near ground-water divides separating Batty Brook from adjacent watersheds; pumping at the well field may shift the location of these divides. The lateral model boundaries included perennial streams: Pascoag, Clear, and Nipmuc Rivers on the west, Sucker Brook on the south, and Chepachet and Branch Rivers on the east. Elsewhere, the edge of the model extended to presumed ground-water divides in the till and bedrock uplands. The active model grid represented an area of 8.6 $mi^2$, consisted of 549 rows and 344 columns, and included a total of 192,598 cells with each cell 50 ft on a side.

Vertical discretization was based on lithology. Layer 1, the top layer, represented surficial deposits. The bottom of layer 1 was the bedrock surface in the valleys (fig. 4); the uneven surface of the bedrock resulted in surficial deposits of variable thickness. The generally thin till in the valleys was incorporated into adjoining stratified deposits for assigning model-input parameters. In upland areas, the bottom of layer 1 was set 15 ft below the land surface, which is consistent with typical till thicknesses in the study area (Hahn and Hansen, 1961). Layer 2, the bottom layer, represents only bedrock. Bedrock was assigned a constant thickness of 200 ft throughout the model beneath the stratified deposits and till.

Model layers were simulated by using a fixed transmissivity, including layer 1, because of the numerical instabilities caused by simulating a thin layer on the sides of steeply sloping hills. In addition, some layer 1 model cells, especially cells representing stratified deposits near the upland contact, may be unsaturated, either during nonpumping, steady-state conditions or because of the large pumping rates used in the calibrated model. In a fixed-transmissivity simulation, MODPATH particles can be tracked from an unsaturated cell representing an area of recharge to a discharge location. The top of the model grid, which is used to determine layer 1 transmissivity, is land surface in the uplands. In the valley, the top of the model grid represented the water table estimated from available ground-water levels and surface-water elevations from surveys and topographical contours on the USGS Chepachet quadrangle. The top of the model grid was only used to calculate transmissivity; the model simulated the saturated thickness and water table.

Several types of boundary conditions were specified in the model to represent areas of discharge and sources of recharge (fig. 8). Interactions between surface water and ground water were simulated as head-dependent flux boundaries in layer 1. Streams that define the perimeter of the model were simulated by using the MODFLOW river package (Harbaugh and others, 2000). The Clear River, from its confluence with the Nipmuc River to where it forms the Branch River, and tributary streams with watersheds contained within the model were simulated by using the stream-routing package (Prudic, 1989) developed for MODFLOW. The stream-routing package accounts for gains and losses of water in each stream cell and routes streamflow from upstream to downstream cells. Streamflow loss to the aquifer, either naturally where the stream flows from low- to high-transmissive sediments or from induced infiltration due to pumping, would cease if simulated streamflow also ceases. Streams that flow into and out of ponds and lakes were simulated as flowing through these water bodies. The model contained a total of 1,177 river cells and 3,436 stream cells.

Surface-water altitudes for the head-dependent flux boundaries were determined from, or interpolated between, topographical contours intersecting streams and from pond and lake altitudes listed on the USGS Chepachet quadrangle. In addition, stage measurements made during this study in May and June 2005 at streambed piezometers, streamflow weirs, and surveyed water surfaces from 23 locations in Batty Brook, the unnamed tributary to Batty Brook, the Clear River at its confluence with Batty Brook, and Suckers Pond were used. Water depths and bed thicknesses of 1 ft were used to determine the top and bottom bed altitudes from surface-water altitudes.

Simulated streams were assigned widths based on field measurements, observations, and estimates. Most simulated stream widths ranged from 3 to 5 ft for small tributaries to 40 ft for the Clear River. In the vicinity of the well field, Batty Brook was simulated as 5 ft wide and the unnamed tributary to Batty Brook was simulated as 4 ft wide.

Streams in the study area, including the Clear River downgradient of the well field and streams in Batty Brook watershed, are generally fast-moving with sand and gravel bed sediments. An exception to this in the well-field area is a small wetland through which the unnamed tributary flows downgradient of the weir. A vertical hydraulic conductivity value of 1 ft/d was used to represent coarse-grained bed sediments; a value of 0.1 ft/d, which is at the low end of reported values for fine-grained bed sediments, was used to represent wetland deposits beneath the unnamed tributary to Batty Brook. Streambed conductances simulated in the model, therefore, ranged from 20 $ft^2/d$ for the small stream flowing over the wetland near the well field to 2,000 $ft^2/d$ for the Clear River underlain by coarse bed sediments.

Recharge rates were distributed based on surficial geology and hydrography (fig. 8); recharge values used in the model are effective rates which account for the effects of ground-water evapotranspiration. A recharge rate of 26 in/yr based on long-term averages at the Branch and Nipmuc River streamflow-gaging stations was applied to the stratified deposits. For impervious surfaces from which part or all of the precipitation is channeled to streams, this rate would have overestimated actual recharge. In the expected contributing area to the well field, however, these impervious areas are likely negligibly small. At the small sand and gravel operation near the well field where evapotranspiration rates may be less than rates in areas covered by vegetation, the model recharge rate may have underestimated the actual recharge. The same recharge rate, 26 in/yr, was applied to upland hillslopes that drain toward the valley with no streams or water bodies at their base. This rate represented both recharge in the uplands and surface runoff that recharges the stratified deposits near the valley-upland contact. Thus all water that is added to the ground-water system through precipitation was accounted for in the model. For upland watersheds and hillslopes with streams or water bodies at the valley-upland contact, a recharge rate of 16 in/yr was applied; this value is less than the basin-wide average effective recharge rate and is at the low end of recharge rates determined for till-dominated watersheds by computerized hydrograph-separation methods.

Horizontal hydraulic conductivity values were assigned on the basis of lithology. The final calibrated value for sand and gravel deposits at the well field was 140 ft/d. Initially one value was used to represent the remaining stratified deposits, which consist mostly of sand, and another value to represent till in the uplands. During model calibration, these surficial deposits were subdivided into additional hydraulic conductivity zones. In general, final hydraulic conductivity values for stratified deposits ranged from 10 ft/d near the upland-valley contact, where saturated thicknesses were about 10 ft or less, to 80 ft/d in central areas of the valleys. Low hydraulic conductivity values were needed to simulate the relatively steep hydraulic gradient between the contact and the main valley streams. Areas of thin stratified deposits may overlie proportionally large quantities of till; this configuration lowers the overall transmissivity. In addition, little data was available to define the bedrock surface accurately in many areas of the modeled area especially along the valley edges. Final hydraulic conductivity values for upland till generally ranged from 3 to 4 ft/d. Bedrock was assigned a value of 0.05 ft/d, which was not altered during model calibration. Model cells containing three large ponds and lakes in the upland and valley were assigned a high hydraulic conductivity ranging from 1,000 to 5,000 ft/d to simulate the flat gradient across these water bodies and realistic ground-water-flow patterns around the water bodies themselves.

## Simulation of Ground-Water Flow

The altitude and configuration of the simulated water table for long-term, nonpumping, steady-state conditions are shown in figure 8. The simulated water-table contours and flow directions are consistent with the conceptual model of ground-water flow in the study area. Ground water flows from topographically high areas and discharges to streams and surface-water bodies. In the uplands, the water table generally parallels the land surface, and simulated ground-water divides generally coincide with watershed divides. The hydraulic gradient is steepest beneath the upland till and stratified deposits near the contact and flattens in the more transmissive valley-fill areas.

A comparison of simulated to measured ground-water altitudes in the stratified deposits, shown in figure 9A, indicates a reasonable agreement. The mean absolute residual is

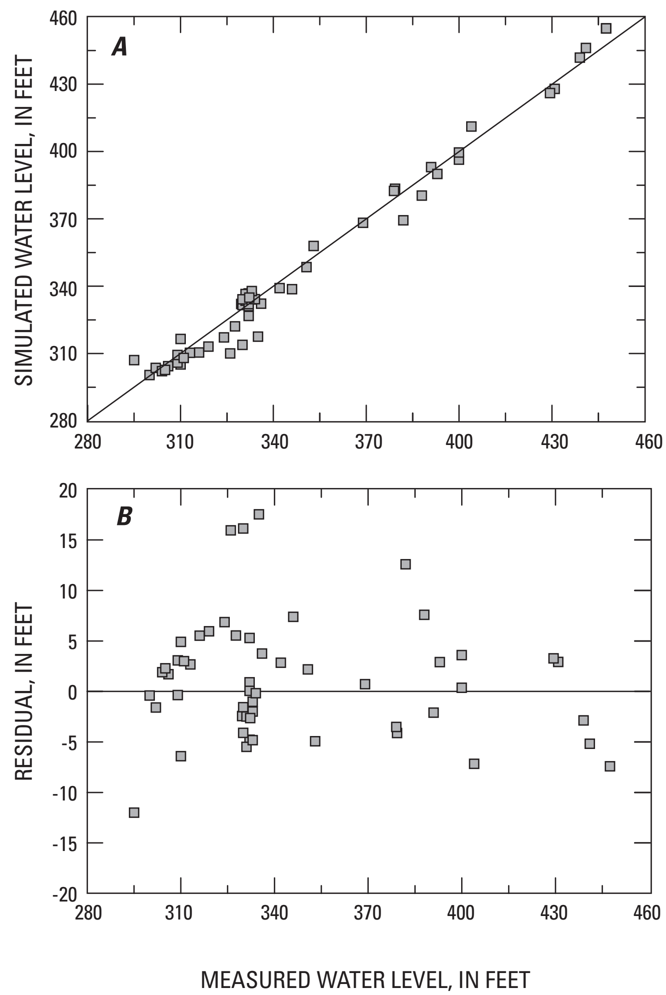



**Figure 9.** (*A*) Relation between simulated and measured ground-water levels and (*B*) residual (measured minus simulated) ground-water levels as a function of measured ground-water levels, Harrisville study site, Rhode Island.

4.5 ft, which is 3 percent of the total difference in ground-water altitude, 152.5 ft, measured at the observation wells. A comparison of residuals (fig. 9B) shows that the differences between simulated and measured water levels are generally randomly distributed around zero. The largest residuals occur near the boundary between the valley-upland contact (fig. 8) in areas with steep hydraulic gradients. The simulated direction of ground-water flow, however, is consistent with expected flow directions in these areas. Large residuals in these areas may be due to spatial variation in transmissivity and recharge rates along the edge of the valley that are not incorporated into the model. Other factors may include the accuracy in determining the exact location and measuring-point altitude from topographic maps for observation wells that were not surveyed to NGVD29.

In addition to ground-water altitudes and flow directions, simulated streamflows also were in good agreement with the long-term average streamflows determined for the two streamflow-gaging stations upgradient of the well field. The difference between simulated flow and estimated long-term average streamflow was 0.03 $ft^3/s$ for both the Batty Brook and unnamed tributary streamflow-gaging stations. By simulating the 2005 average pumping rates for each production well, simulated streamflows were reduced by 0.03 and 0.02 $ft^3/s$ at the Batty Brook and unnamed tributary stations, respectively. These reductions in simulated streamflow are most likely within the uncertainty of the calculated long-term average.

Simulated ground-water flow in the stratified deposits is nearly perpendicular to the main valley streams and nearly parallel to the small tributary streams that drain the uplands and become minimally gaining or losing as they flow over more transmissive stratified deposits; more ground water flows along deeper and longer flow paths to the main valley streams in these areas. An important simulated ground-water divide in the stratified deposits is between the Batty Brook and Sucker Pond watersheds. The simulated ground-water divide between these two watersheds is closer to Sucker Pond than Batty Brook because the stages of the most upstream reaches of Batty Brook are at an altitude lower than the stages of a tributary draining into Sucker Pond from the northwest and of the pond itself.

The simulated long-term nonpumping steady-state ground-water budget for the modeled area, summarized in table 5, indicates that precipitation recharge accounts for most of the total inflow (90 percent). Conceptually this percentage represents both direct infiltration of precipitation and surface runoff from hillslopes that recharges the valley near the contact. Streamflow loss from natural infiltration accounts for the remaining inflow (10 percent); most of this streamflow loss is from tributaries where they flow over the stratified deposits and at the downstream ends of ponds and lakes. Ground-water discharge is to the streams and surface-water bodies. The simulated water budget for only the stratified deposits is also shown in table 5. Precipitation recharge directly on the valley contributes most of the inflow (62 percent), but upland sources, either directly or indirectly, contribute a significant amount (38 percent). These upland sources include lateral and vertical flow from till and bedrock (26 percent) and streamflow loss from tributary streams (12 percent).

**Table 5.** Simulated steady-state average annual hydrologic budget for nonpumping conditions, Harrisville study site, Rhode Island.

[$ft^3/s$, cubic feet per second]

| Hydrologic budget component | Flow rate ($ft^3/s$) |
|---|---|
| **Modeled area** | |
| **Inflow** | |
| Recharge | 14.2 |
| Streamflow loss | 1.6 |
| Total inflow | 15.8 |
| **Outflow** | |
| Streamflow | 15.8 |
| Total outflow | 15.8 |
| **Glacial stratified deposits only** | |
| **Inflow** | |
| Recharge | 7.6 |
| Streamflow loss | 1.5 |
| From till | 2.5 |
| From bedrock | .6 |
| Total inflow | 12.2 |
| **Outflow** | |
| Streamflow | 12.0 |
| To till | .1 |
| To bedrock | .1 |
| Total outflow | 12.2 |

## Areas Contributing Recharge to Production Wells

Simulated areas contributing recharge to the Harrisville Central Street well field were determined on the basis of the calibrated steady-state model, for simulated pumping conditions, and tracking of pathlines with the MODPATH particle-tracking program. The locations and extents of the simulated areas contributing recharge to each production well pumping at the 2005 average rate and the maximum rate (table 1) are shown in figures 10 and 11. The total maximum pumping rate for the well field, 600 gal/min, is 2.7 times the total 2005 average rate of 224 gal/min. The total sizes of the areas contributing recharge to the well field and percentages of the total water withdrawn from each water source for the well field are listed in table 6.

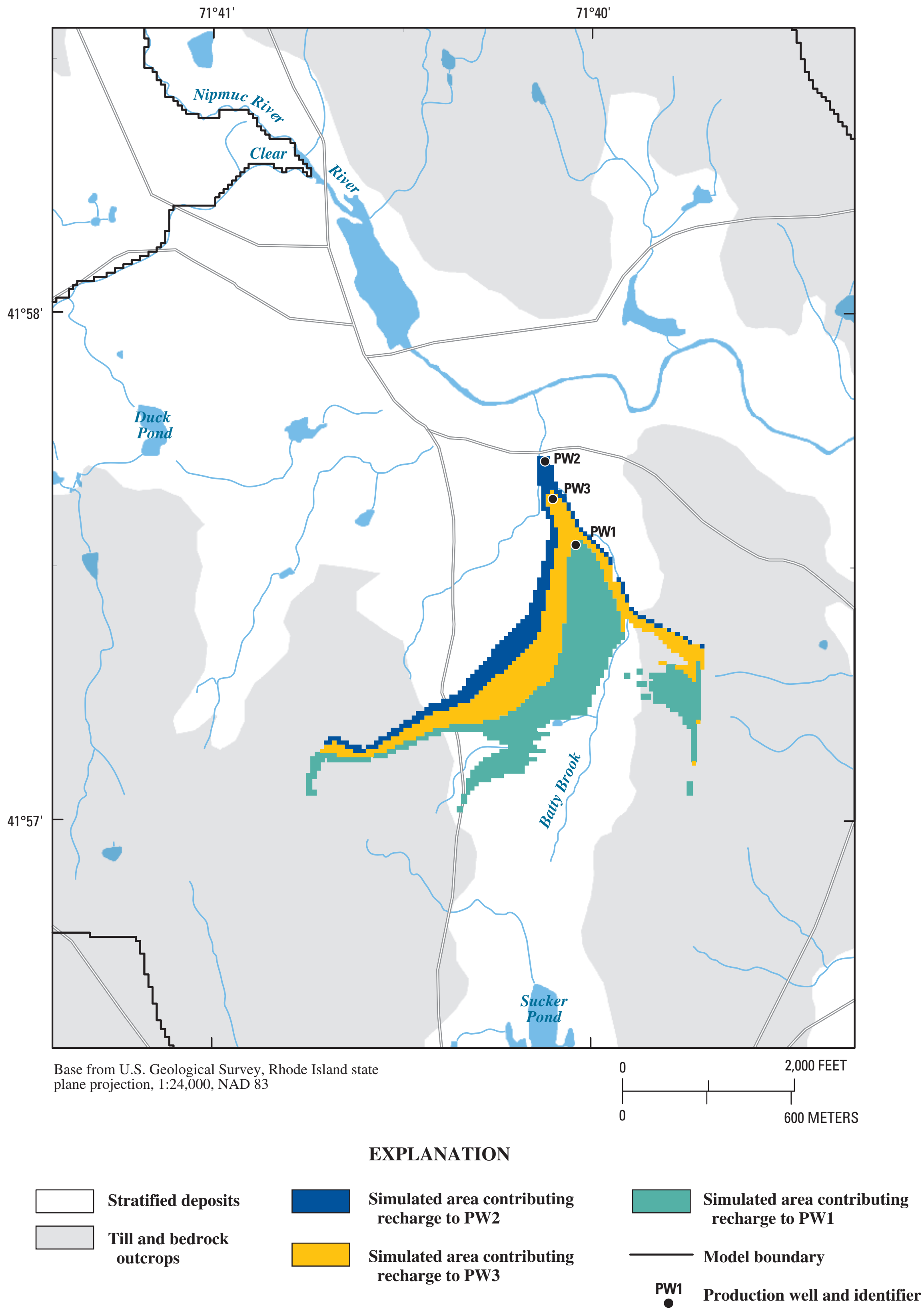



**Figure 10.** Simulated area contributing recharge to the Harrisville well field at its average pumping rate of 224 gallons per minute, Harrisville study site, Rhode Island.

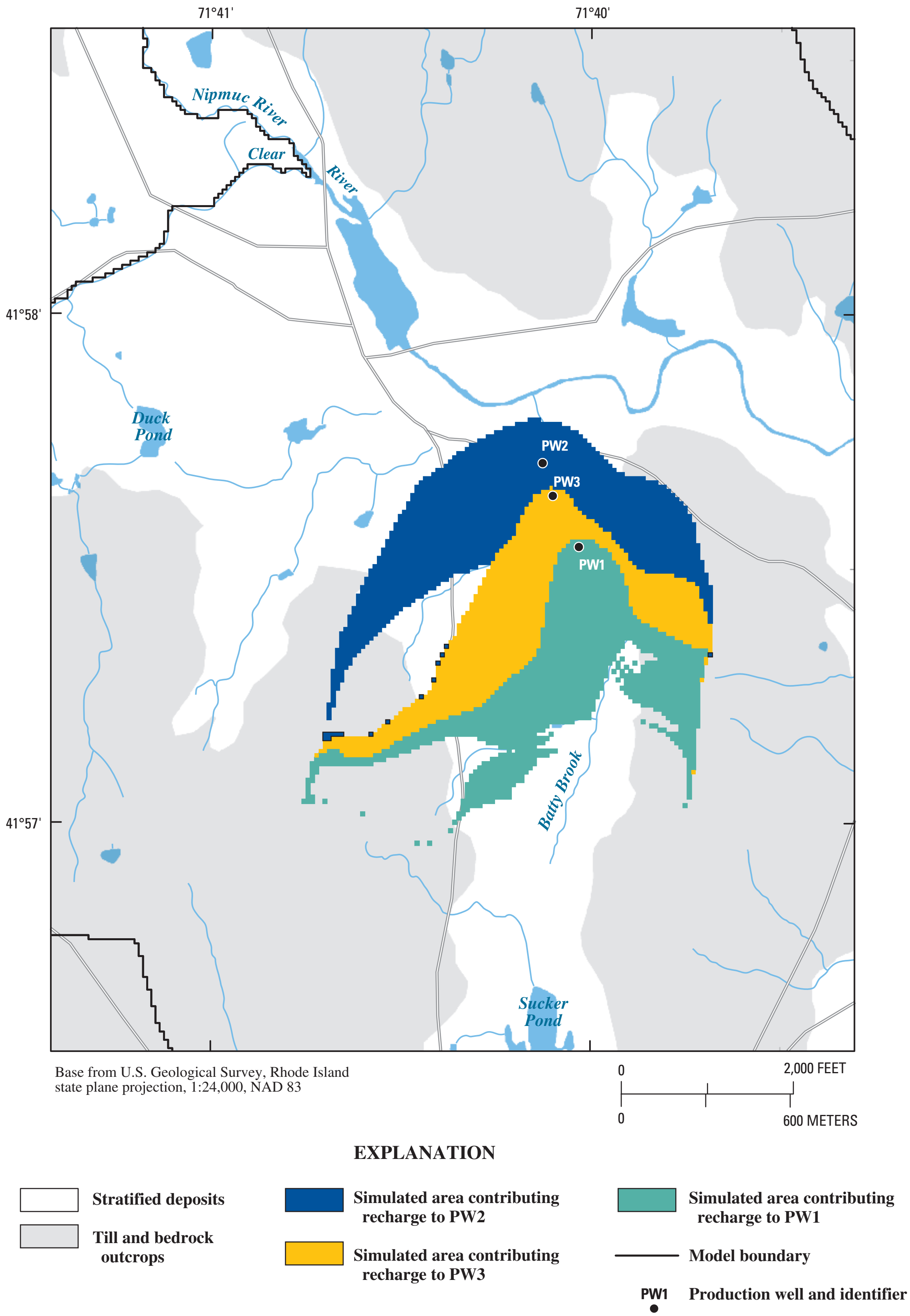



**Figure 11.** Simulated area contributing recharge to the Harrisville well field at its maximum pumping rate of 600 gallons per minute, Harrisville study site, Rhode Island.

**Table 6.** Sizes of areas contributing recharge to the Harrisville production well field (Central Street) and the percentages of water withdrawn from different sources, Harrisville study site, Rhode Island.

[gal/min, gallons per minute; mi$^2$, square mile]

| Model scenario | Size of area contributing recharge (mi$^2$) | Direct precipitation recharge and upland runoff (percent) | Infiltration of surface water (percent) |
|---|---|---|---|
| 224 gal/min | 0.17 | 62 | 38 |
| 600 gal/min | .44 | 63 | 37 |
| 600 gal/min and vertical hydraulic conductivity of streambed × 0.5 | .52 | 75 | 25 |
| 600 gal/min and vertical hydraulic conductivity of streambed × 2 | .37 | 52 | 48 |
| 600 gal/min and hydraulic conductivity of stratified deposits × 0.75 | .44 | 63 | 37 |
| 600 gal/min and hydraulic conductivity of stratified deposits × 1.25 | .44 | 62 | 38 |
| 600 gal/min and recharge rates × 0.75 | .63 | 67 | 33 |
| 600 gal/min and recharge rates × 1.25 | .37 | 67 | 33 |

The total area contributing recharge for the average pumping rate covers about 0.17 mi$^2$ and extends in a generally southward direction from the well field to ground-water divides in the uplands. The contributing area upgradient of the well field extends beneath and beyond small streams in two areas where the simulated stream does not capture all the water entering the model cell or the stream cell simulates as a slightly losing reach. The well field derived most of its water from direct precipitation recharge—intercepted ground water that normally discharges to streams—but 38 percent of the pumped water is from Batty Brook and its tributaries. The shape of the area contributing recharge and the source of water to an individual well are strongly affected by the other two pumping wells. The most upgradient well, PW1, derives a greater percentage of its water from ground water compared to the other two wells, whereas PW2, the most downgradient well, derives a greater percentage of its water from the streams than the other two wells.

At the maximum withdrawal rate of 600 gal/min, the area contributing recharge is 0.44 mi$^2$. The increased pumping rate is balanced by expansion of the area contributing recharge to intercept additional ground water that would have normally flowed to Batty Brook, its tributaries, and to the Clear River, and by inducing additional surface water, primarily from stream reaches of Batty Brook and the unnamed tributary in the vicinity of the well field. The percentage of pumped water derived from streamflow (37 percent), however, is about the same percentage as for the average pumping rate.

As was mentioned previously in the Hydrology section, the maximum pumping rate exceeds available recharge in the Batty Brook watershed. Thus, most of the precipitation recharge in the watershed is withdrawn by the well field at the maximum rate, either directly by intercepted ground water or indirectly by streamflow loss. More than 80 percent of the precipitation recharge that discharges to upstream reaches in Batty Brook watershed is withdrawn by the wells by inducing flow from stream reaches near the well field.

Similar to the average pumping rate, the shape of the contributing area and source of water to an individual well is strongly affected by nearby pumping. In contrast to the average pumping rate, however, the most downgradient well, PW2, derives a greater percentage of its water from ground water than the other two wells; the area contributing recharge to PW2 extends down valley toward the Clear River to capture ground water that would normally discharge to the Clear River and its tributaries. At the maximum pumping rate, it is the middle well PW3 that derives a greater percentage of its water from the stream than the other two wells.

Simulated traveltime estimates from recharging locations to the production wells for the maximum pumping rate, based on porosities of 0.35 for stratified deposits and till and 0.02 for bedrock, are shown in figure 12. Traveltimes ranged from less than 6 months to more than 100 years; 93 percent of the traveltimes were 10 years or less. Water that recharges the stratified deposits at the well field from direct precipitation recharge and from streamflow loss has the shortest traveltimes,

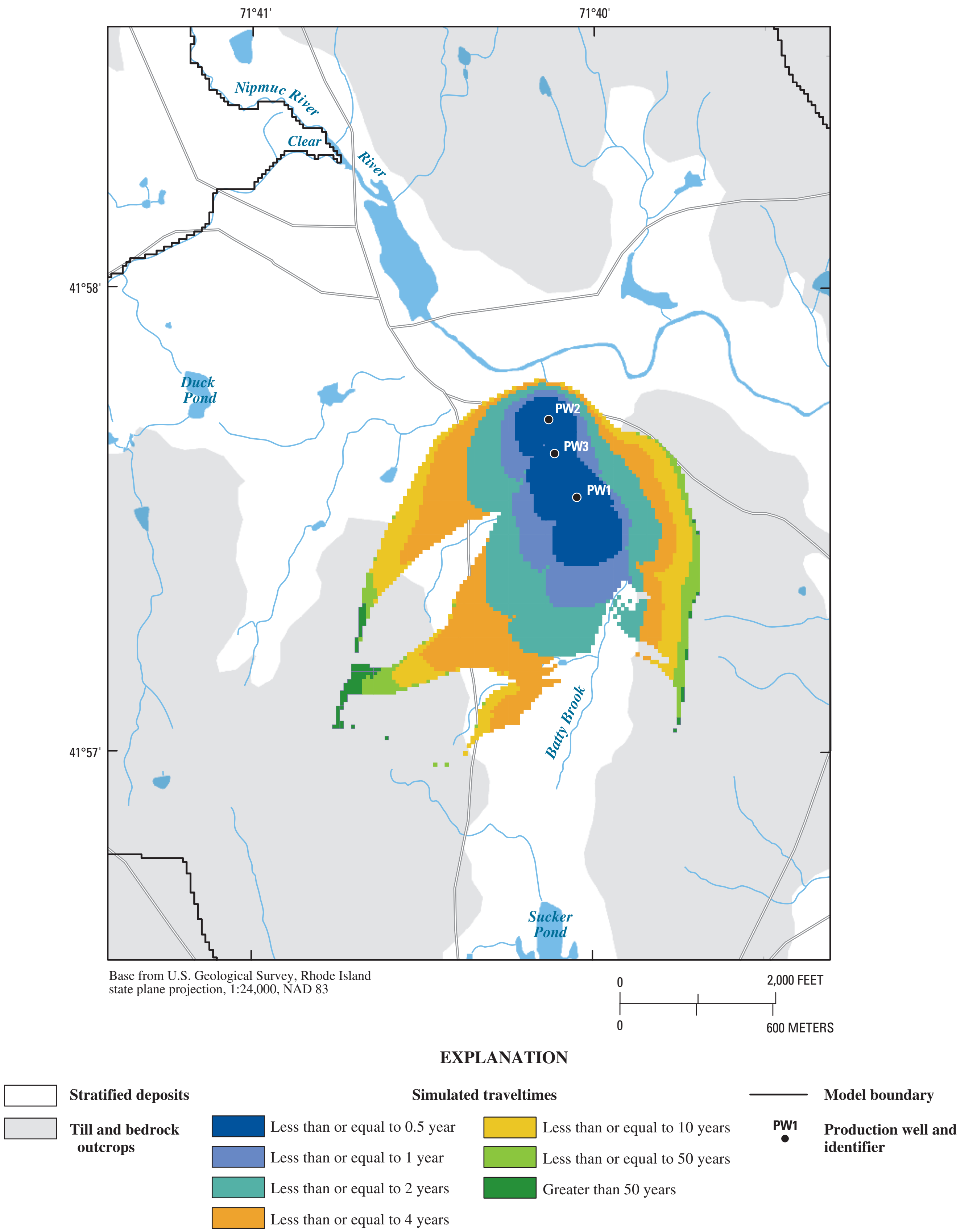



**Figure 12.** Simulated traveltimes to the Harrisville well field at its maximum pumping rate of 600 gallons per minute, Harrisville study site, Rhode Island.

whereas recharge originating from areas near the ground-water divides in the southern part of Batty Brook watershed has the longest traveltimes.

The area contributing recharge to the Harrisville Eccleston well field extends in a generally westward direction from the Eccleston well field in the Clear River valley (Dufresne-Henry, Inc., 2001). The southeast extent of the Eccleston well-field contributing area, near Duck Pond (fig. 2), is about 0.7 mi from the western extent of the Harrisville Central Street well-field contributing area.

## Sensitivity and Uncertainty Analysis

A sensitivity analysis of the effects of selected values of hydraulic properties and recharge on the simulated areas contributing recharge and the sources of water to the well field was done for the maximum well-field withdrawal rate of 600 gal/min. Reasonable alternative values were chosen to provide insights into the effects of these values on the area contributing recharge to a well field in a small watershed in a narrow, valley-fill setting. The analysis provides an estimate of the uncertainty in the size, shape, and location of the contributing area by comparing it to the delineated contributing areas.

The hydraulic connection between streams in Batty Brook watershed and the aquifer was sequentially decreased by 50 percent and increased by a factor of 2 by altering the vertical hydraulic conductivity of streambed sediments. Changes were made only to stream cells in the vicinity of the well field in the area of infiltration so that approximately the same quantity of streamflow entered the well-field area and was available for infiltration. The reduced hydraulic connection between the stream and the aquifer caused the quantity of stream water withdrawn at the well field to decrease by 12 percent (from 37 to 25 percent) and the area contributing recharge to the well field to increase from 0.44 to 0.52 $mi^2$ (table 6 and fig. 13). The contributing area expanded primarily downvalley toward the Clear River and includes an isolated area on the opposite side and north of the river from the well field and south of a ground-water divide in the uplands. The area contributing recharge north of the Clear River includes till uplands and stratified deposits near the contact; this recharge travels along deeper and longer ground-water flow paths than recharging water that originates closer to the valley center. Under nonpumping conditions, this water would eventually discharge to the Clear River, but under pumping conditions is withdrawn by the well field. With an increased hydraulic connection, all available streamflow in Batty Brook and the unnamed tributary infiltrated; thus, the percentage of surface water withdrawn by the well field increased by 11 percent from 37 to 48 percent (table 6). The area contributing recharge decreased from 0.44 to 0.37 $mi^2$ primarily in the downvalley direction from the well field (fig. 13).

The hydraulic conductivity of the stratified deposits was decreased and increased by 25 percent. At this range of hydraulic conductivity, the simulated size of the area contributing recharge and the percentages of water from different sources withdrawn at the well field are the same as for the base-model simulations, but the location of the contributing area was slightly different (table 6 and fig. 14). By decreasing hydraulic conductivity of the stratified deposits, the hydraulic gradient between ground water and surface water increased, thereby increasing ground-water discharge to upstream reaches of Batty Brook watershed. Because of the stronger component of ground-water flow to these upstream reaches, the area contributing recharge to the well field shifted in a northward direction and included a small area in the till north of the Clear River. Increasing the hydraulic conductivity caused the opposite effect on the location of the contributing area: a stronger downvalley component of ground-water flow and less discharge to the upstream reaches, and thus a southward shift in the contributing area.

Annual recharge rates were also decreased and increased by 25 percent across the modeled area. The area contributing recharge increased from 0.44 to 0.63 $mi^2$ when recharge was reduced and decreased to 0.37 $mi^2$ under higher recharge rates (table 6 and fig. 15). Surface-water infiltration for both lower and higher recharge rates was 33 percent of the total water pumped; this amount is 4 percent less than the base-model simulation. The reduced recharge rate resulted in the largest simulated contributing area to the well field for the range of model-input values considered. The area contributing recharge expanded in almost all directions from the opposite side of the Clear River north of the well field to an area that is within both till uplands and stratified deposits. Simulated recharge water that travels along both shallow and deep flow paths before discharging to the Clear River under nonpumping conditions travels instead beneath the Clear River to the well field under pumping conditions. A small quantity of pumped water (less than 1 percent) is also from the Clear River itself. The small streams in Batty Brook watershed were sensitive to the altered recharge rates; ground-water discharge to these streams upgradient of the well field at the lower recharge rate was less than one-half that at the higher rate. At the lower recharge rate, all available streamflow in Batty Brook and the unnamed tributary infiltrated, but because less ground water discharged to these streams upgradient of the well field under the reduced recharge rates, the percentage of surface water pumped at the well field was less. Hence, less streamflow near the well field also was a factor in the expanded contributing area in addition to the reduced recharge rate. In contrast, for simulated pumping wells that derived part of their water from nearby surface water, where the quantity of available surface water was large in comparison to the pumping rate, reduced recharge rates resulted in both an increase in contributing area and the percentage of surface-water infiltration (Friesz, 2004).

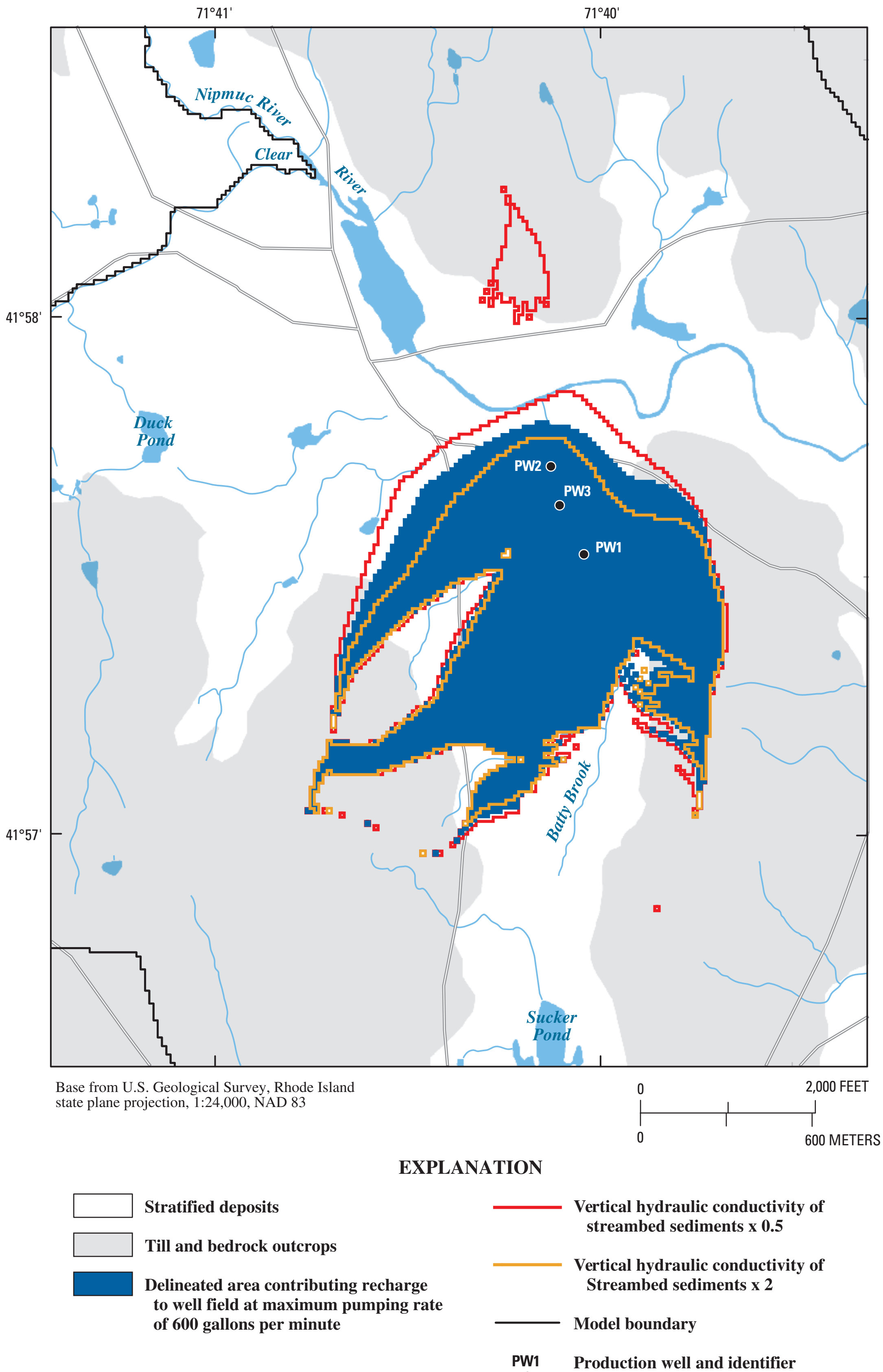



**Figure 13.** Sensitivity analysis of the effects of multiplying the vertical hydraulic conductivity of streambed sediments at the well-field site by 0.5 and by 2, Harrisville study site, Rhode Island.

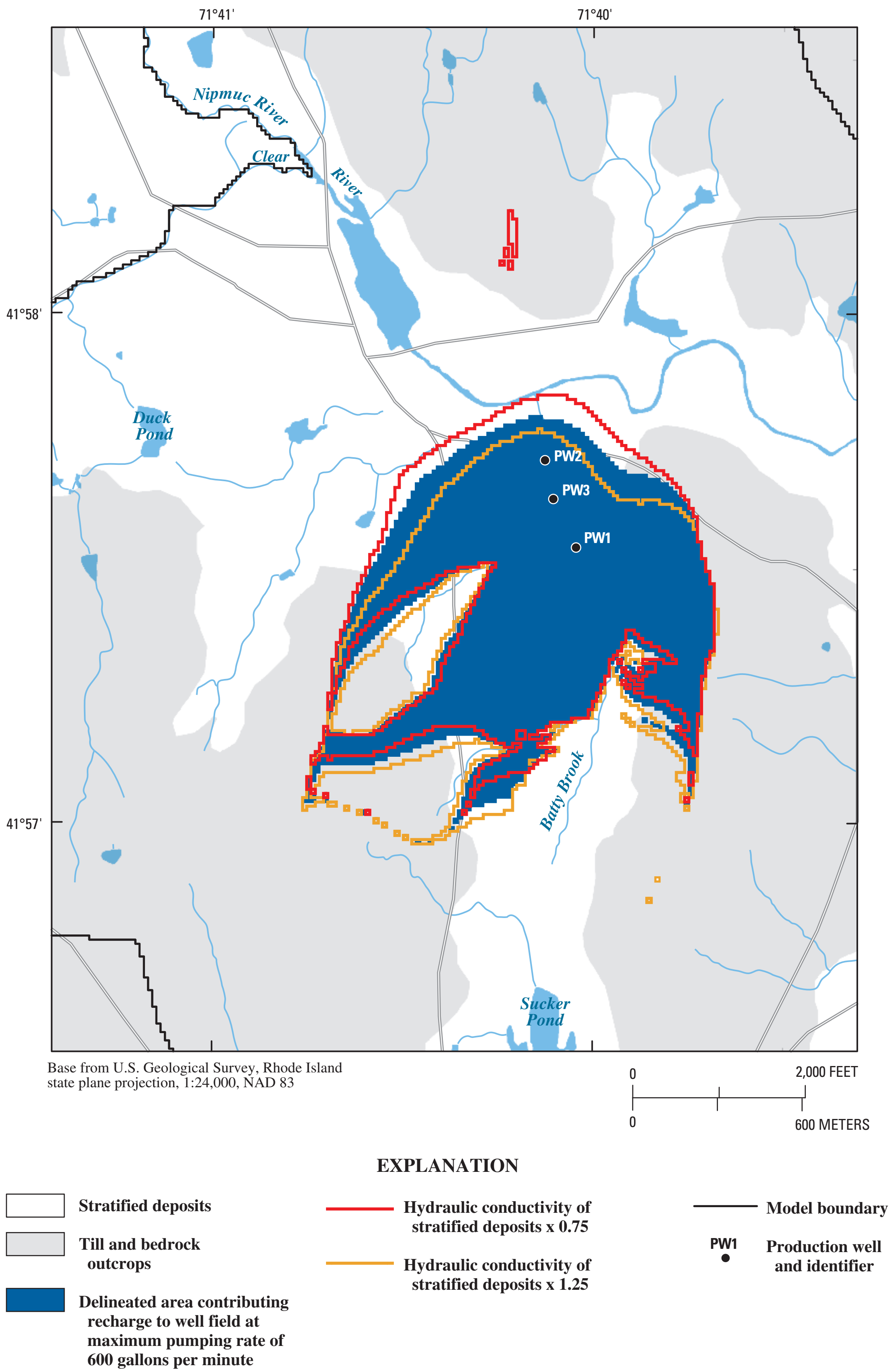



**Figure 14.** Sensitivity analysis of the effects of multiplying the hydraulic conductivity of stratified deposits by 0.75 and by 1.25, Harrisville study site, Rhode Island.

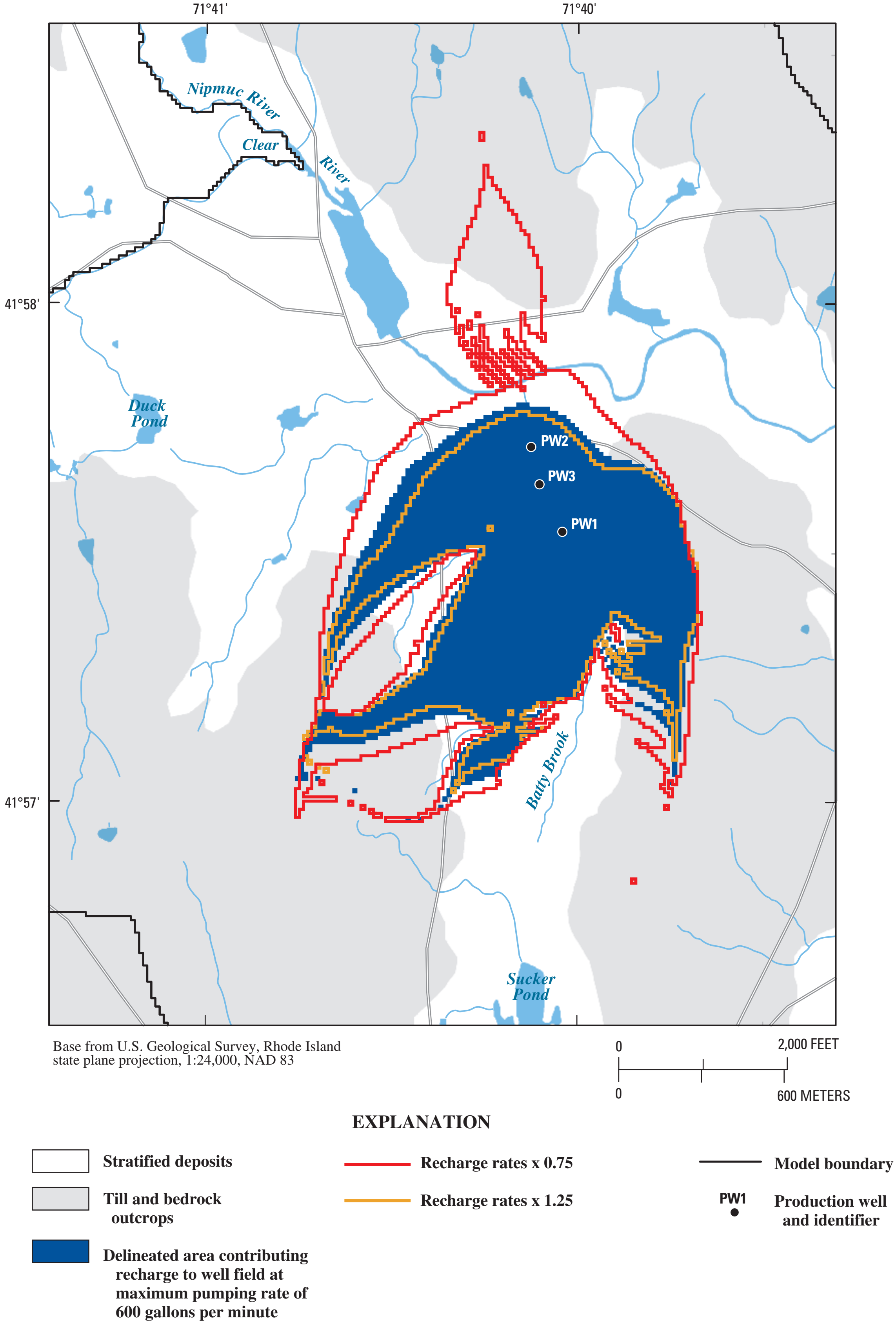



**Figure 15.** Sensitivity analysis of the effects of multiplying recharge rates by 0.75 and by 1.25, Harrisville study site, Rhode Island.

# Richmond Study Site

The Town of Richmond production well field is adjacent to the Wood River in southwestern Rhode Island (figs. 1 and 16). The well field is in a broad (1.2-mi-wide) valley-fill setting bordered by extensive upland till and bedrock. The geographic extent of the study area includes perennial surface-water bodies and watershed divides that served as boundaries for the numerical model. These boundaries include Brushy Brook, Locustville Pond, and an unnamed tributary in the southwest; a section of the Wood River in the south; and watershed divides generally in the uplands where surface-water and ground-water divides are most likely the same, in the southeast, east and west. The watershed boundary for the Wood River near Arcadia streamflow-gaging station forms the northern extent; this watershed boundary is in both upland and valley-fill deposits. The large model extent minimizes the effect of model boundaries on simulated heads near the area likely to be within the contributing area of the well field and incorporates uplands west and east of the well field directly in the model. Land use in the general area of the well field includes rural residential, agriculture, and forest. Some of the forestland is protected in Arcadia State Park Management Area. Land use also includes a sand and gravel mining operation about 0.4 mi northwest of the well-field site.

The Richmond production well field consists of two wells 360 ft and 580 ft east of the Wood River; characteristics of the supply wells are listed in table 1. The production wells are screened in the lower part of a coarse-grained sediment unit with saturated thickness greater than 60 ft. PW1 was constructed in 1985 to replace contaminated residential wells in the Village of Wyoming 1.5 mi south of the well-field site, whereas PW2, a small-diameter production well, was added in 1995 as a backup to PW1. Areas contributing recharge were determined for the maximum well-field withdrawal rate of 675 gal/min and, in addition, one-half the maximum withdrawal rate to determine the effects of pumping rates on the size and location of the contributing area.

Water levels and streamflows were measured periodically from May 2004 to July 2005 to provide information concerning average hydrologic conditions. Water-level measurements were made in existing observation wells and in the Wood River at the well-field site. Streamflow measurements were made at three sites in Baker Brook, which drains an upland watershed before flowing over the stratified deposits about 0.4 mi north of the well field. Lithologic logs and seismic-refraction surveys, mainly from USGS reports and files, were compiled to define the altitude of the bedrock surface and sediment size of the stratified deposits.

## Geology

In the Richmond study area, till-covered bedrock uplands border the Wood River valley and its tributary Brushy Brook valley. Glacial-meltwater deposits as much as 200 ft thick are in these valleys (fig. 16). Postglacial sediments overlie glacial deposits in flood-plain and wetland areas. Bedrock beneath the study area consists predominantly of Hope Valley alaskite gneiss in the southwestern part of the study area and the Scituate plutonic suite in the northeastern part of the area (Moore, 1958). These rock units were more recently characterized as late Proterozoic alaskite and granite gneisses of the Sterling and Esmond plutonic suites intruded by younger Devonian-age granite of the Scituate plutonic suite (Hermes and others, 1994). The bedrock valleys of the Wood River and Brushy Brook are partially filled with glacial-meltwater sediments, and the altitude of the bedrock surface beneath these valleys is shown on figure 16. Bedrock-surface contours were constructed on the basis of locations of bedrock outcrops, knowledge of bedrock structure, interpretation of glacial-till thickness from topography and aerial photographs, and all available well data and seismic-refraction surveys.

The distribution of glacial deposits shown in figure 16 was modified from Feininger (1962). Glacial deposits include subglacially deposited till and stratified glacial-meltwater deposits. These materials overlie the bedrock surface and range from a few feet to as much as 200 ft thick in parts of the Wood River valley. In the vicinity of the Richmond production well field, glacial deposits are generally about 75 ft in thickness. The distribution of surficial materials between the land surface and the bedrock surface is shown on cross sections C-C´ and D-D´ (fig. 17). The cross sections illustrate the characteristic vertical succession of glacial till, glacial-meltwater deposits (sand and gravel; sand; very fine sand, silt, and clay) and postglacial deposits (wetland and alluvial). Most of these materials are deposits of the last two continental ice sheets that covered New England during the middle and late Pleistocene. Most were laid down during the advance and retreat of the last (late Wisconsinan) ice sheet, which reached its terminus on Long Island, N.Y., about 21,000 radiocarbon years ago, and was retreating northward through southern Rhode Island between 18,000 and 17,000 radiocarbon years ago (Stone and Borns, 1986; Boothroyd and others, 1998; Stone and others, 2005).

Glacial till in the map area was deposited directly by glacier ice and is characterized as a nonsorted, nonlayered, relatively compact mixture of sand, silt, and clay with variable amounts of stones and large boulders. Till blankets the bedrock surface in most places and is generally less than 10–15 ft thick. Many places within the area shown as “till and bedrock outcrops” (fig. 16) are characterized by bedrock rather than till at the land surface. Till also commonly underlies glacial stratified deposits in the valleys where it is generally less than 10 ft thick.

Glacial-meltwater deposits in the Wood River valley with surface altitudes of about 135 ft in the southern part of the study area rising to about 185 ft in the northern part consist of gravel, sand and gravel, sand, and fine-grained materials. The surficial geologic map of the Hope Valley quadrangle (Feininger, 1962) describes the meltwater deposits in the study area as a single glaciofluvial unit deposited in large part on

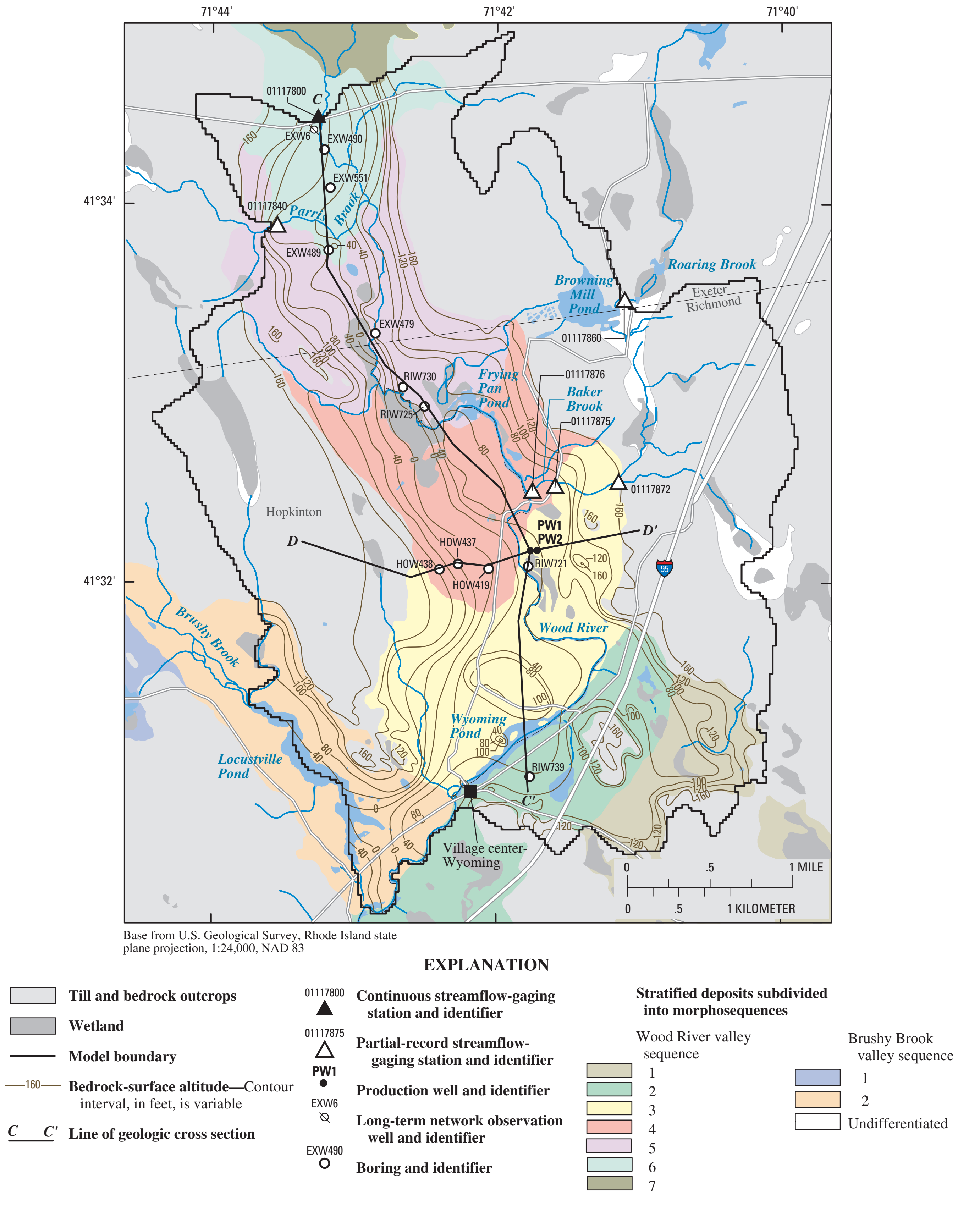



**Figure 16.** Production wells, section lines, selected borings and observation wells, model extent, surficial geology, and bedrock-surface contours, Richmond study site, Rhode Island.

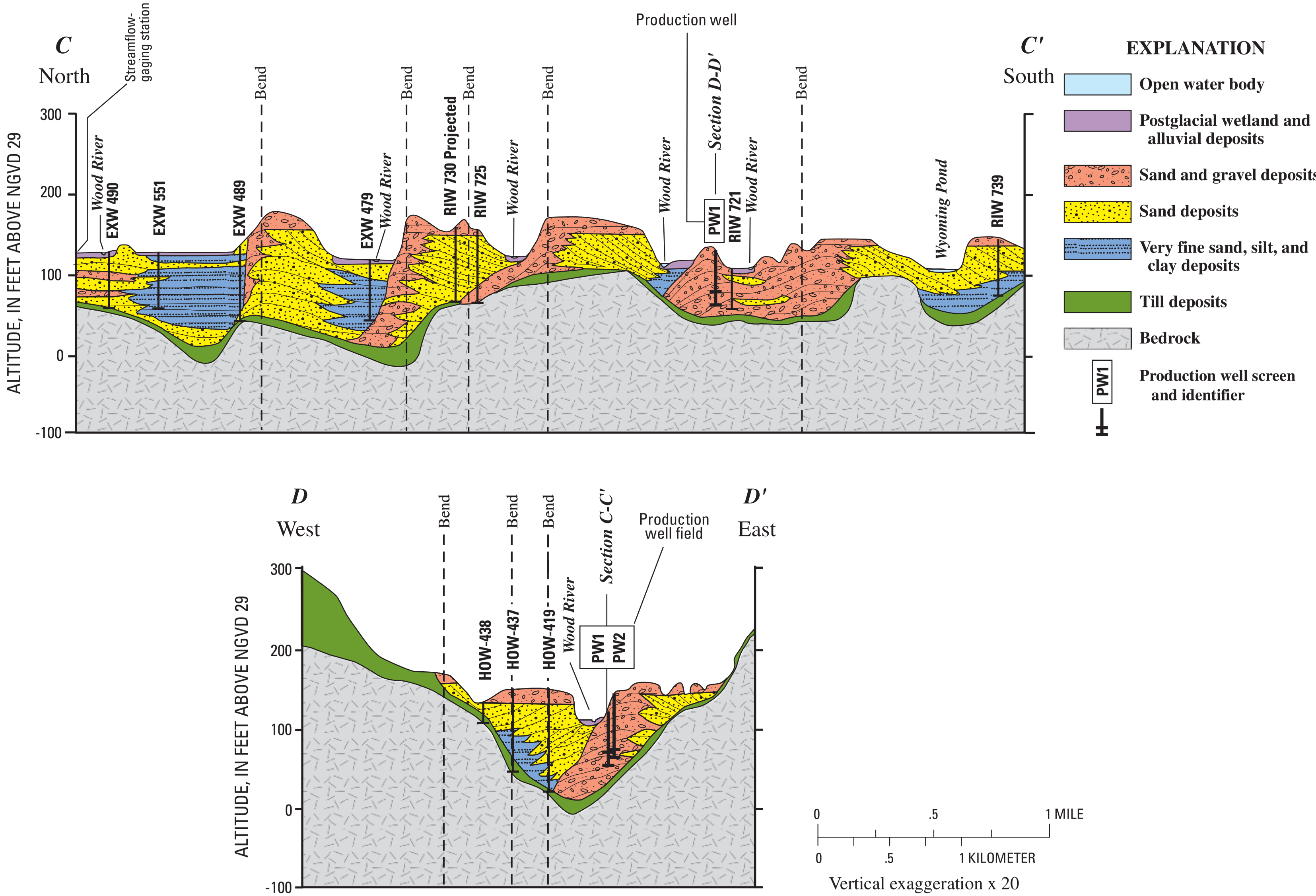



**Figure 17.** Geologic cross sections (lines of sections C-C′ and D-D′ are shown in figure 16), Richmond study site, Rhode Island.

stagnant ice and with an unpredictable, highly variable range in grain size. Recent analysis of these deposits on the basis of the regionally established geologic concepts of stagnation-zone retreat and morphosequence deposition (Koteff and Pessl, 1981; Stone and others, 2005) coupled with textural data derived from available well logs, however, allows for a more predictable and useful depiction of textural variations within these highly complex glacial-meltwater deposits.

A series of ice-marginal, sediment-dammed ponds developed in the Wood River valley in which ice-marginal deltaic and lake-bottom sediments were deposited as the glacier front retreated northward through the area (see discussion of this meltwater depositional process in Stone and others, 2005). Section C-C´ (fig. 17) shows the distribution of collapsed and noncollapsed gravelly deltaic-topset beds, sandy deltaic-foreset beds, and fine-grained lake-bottom deposits of five shingled deposits (morphoseqences) related to five successive (from south to north) ice-margin positions in the valley. The Richmond production wells are screened in the coarse-grained ice-proximal part of the earliest morphosequence in this part of the valley; these coarse-grained deposits are overlain to the north and west by finer grained delta foreset sands and lake-bottom fines of the next (younger) morphosequence to the north (see sections C-C´ and D-D´, fig. 17).

Postglacial deposits locally overlie glacial deposits and include flood-plain alluvium along rivers and streams and organic peat and muck (wetland deposits) in low-lying closed depressions. These deposits are illustrated on the geologic sections (fig. 17), but the alluvial deposits are not shown on the map (fig. 16).

## Hydrology

The Richmond well field is adjacent to the Wood River, which drains a southward-trending valley (fig. 16). Stratified deposits form a moderately broad valley bounded on the west and east by till-covered bedrock uplands drained by numerous perennial streams. The stream network shown in figure 16 is delineated at the 1:24,000 scale except in and near the area expected to be within the contributing area of the well field, where the 1:5,000 scale network was used. This includes Baker Brook, where streams in the uplands were more extensive at the 1:5,000 scale, and a tributary north of Baker Brook, which was not in the 1:24,000-scale network. Two streams that flow into Browning Mill Pond, one of which is adjacent to Baker Brook watershed and the other a long stream, were also used in the ground-water flow model to simulate heads and flow directions in the uplands accurately. Dams built across streams created several ponds including Frying Pan Pond north and Wyoming Pond south of the well-field site.

The production wells are screened in sand and gravel sediments east of the Wood River and north of a riparian wetland. The saturated thicknesses of the stratified deposits in the well-field area range from about 100 ft in the preglacial-valley axis west of the Wood River to more than 60 ft at the well-field site to zero near till and bedrock exposed within the valley east of the site. An average hydraulic conductivity of 800 ft/d was estimated for these sand and gravel deposits from a short-term (45 hours) aquifer test at a well midway between the river and PW1, whereas the value estimated from the lithologic log was 200 ft/d (Dickerman and Bell, 1993).

A major potential source of water to the well field includes direct infiltration of precipitation. Streamflow records from three nearby long-term streamflow-gaging stations provided a guide in assigning recharge rates in the model area, (figs. 1 and 16, table 7). The drainage area of the Wood River at Hope Valley station (01118000) includes the model area, and the Wood River near Arcadia station (01117800) is at the northern model boundary. Both of the drainage areas for the Wood River stations include surficial deposits of till and stratified deposits. The Pendleton Hill Brook station, about 8 mi southwest of the study site, drains a small, predominantly till watershed. Mean annual streamflow (precipitation minus evapotranspiration) is equivalent to about 29 in/yr over all three drainage areas. Mean annual ground-water discharge (effective recharge) for the Wood River stations computed by the hydrograph-separation method PART (Rutledge, 1998) was about 25 to 26 in/yr or 85 to 87 percent of total streamflow. Effective recharge for the Pendleton Hill Brook station was less, about 21 in/yr or 74 percent of total streamflow. These rates represent averages over the entire watershed, including areas of stratified deposits, till, surface-water bodies, wetlands, and a variety of land uses. The difference between mean annual streamflow and ground-water discharge is surface runoff from areas that reject infiltration of precipitation. These areas include impervious surfaces, surface-water bodies, wetlands, and areas where the water table is at the land surface seasonally, such as some till areas.

A second potential source of water to the well field is induced infiltration of river water from the nearby Wood River. A visual inspection of the riverbed sediments, along with measurements made by using a hand-held steel rod, indicated that the riverbed adjacent to the well field is composed of loose sand and gravel except near its banks, where fine-grained bottom sediments ranged from 0.6 to 1.6 ft thick. A cross section through the river 1,200 ft downstream of the well field by Gonthier and others (1974) showed similar results. The amount of river water available for infiltration under average annual conditions greatly exceeds the maximum withdrawal rate for the well field, 675 gal/min or 1.5 $ft^3/s$. Mean annual streamflow (118 $ft^3/s$) and ground-water discharge (100 $ft^3/s$) for the 54.9-$mi^2$ drainage area of the Wood River upstream of the well-field site are based on streamflow characteristics for the Wood River at Hope Valley station. The maximum withdrawal rate for the well field is less than 2 percent of these mean annual streamflow and ground-water-discharge rates. Drawdowns in observation wells, including one near the river during the aquifer test by Dickerman and Bell (1993), did not indicate any vertical leakage from surface water; however, this aquifer test was of short duration.

**Table 7.** Streamflow and drainage-area characteristics of selected streamflow-gaging stations in and near the Richmond study site, Rhode Island.

[USGS, U.S. Geological Survey. USGS station number: Locations shown on figures 1 and 16; mi$^2$, square mile; ft$^3$/s, cubic feet per second; in/yr, inches per year; PART (Rutledge, 1998) hydrograph-separation method. Ground-water discharge index is mean annual ground-water discharge divided by mean annual streamflow.]

| USGS station number | Station name | Drainage area (mi$^2$) | Area of glacial stratified deposits (percent) | Period of record analyzed | Mean annual stream-flow (ft$^3$/s) | Mean annual stream-flow (in/yr) | Mean annual ground-water discharge PART (ft$^3$/s) | Mean annual ground-water discharge PART (in/yr) | Ground-water-discharge index (percent) |
|---|---|---|---|---|---|---|---|---|---|
| 01117800 | Wood River near Arcadia, R.I. | 35.2 | 23 | 1965–80; 1983–03 | 76.7 | 29.6 | 66.8 | 25.8 | 87 |
| 01118000 | Wood River at Hope Valley, R.I. | 72.4 | 26 | 1942–03 | 155.8 | 29.2 | 132.5 | 24.9 | 85 |
| 01118300 | Pendleton Hill Brook near Clarks Falls, Conn. | 4.02 | 8.4 | 1959–03 | 8.6 | 29.1 | 6.37 | 21.5 | 74 |

Another potential source of water to the well field is natural or induced infiltration from tributaries that cross transmissive stratified deposits from upland areas, such as Baker Brook north of the well field. Streamflow measurements were made at three partial-record sites in Baker Brook: one site is at the valley-upland contact (01117872), and the other two sites are 2,300 ft (01117875) and 3,200 ft (01117876) downstream of the contact (fig. 16). Ten sets of measurements made at the contact and the closer downstream site from May 2004 to July 2005 indicated that net streamflow between sites ranged from 0.04 ft$^3$/s gain to 0.23 ft$^3$/s loss. Additional measurements during the summer of 2004 at the farther downstream site near the confluence with the Wood River showed a maximum net loss of 0.32 ft$^3$/s. At mean annual ground-water levels, based on long-term observation well EXW6 (fig. 16), net loss was 0.12 ft$^3$/s between the contact and the closer downstream site (with a range of 0.06 to 0.18 ft$^3$/s net loss based on measurement accuracy). At near mean annual ground-water levels, loss ranged from 0.11 to 0.14 ft$^3$/s. If the net loss of 0.12 ft$^3$/s at average ground-water levels is applied to the total distance between the contact and the Wood River (3,300 ft), the total net loss for this reach is equivalent to 0.17 ft$^3$/s, or 76 gal/min. Thus, the estimated net loss from Baker Brook as it flows over the stratified deposits corresponds to 11 percent of the maximum well-field withdrawal rate of 675 gal/min.

Streamflow measurements made at the upland-valley contact in Baker Brook and available streamflow measurements from the Parris Brook (01117840) and Roaring Brook (01117860) partial-record sites from previous and ongoing USGS studies (fig. 16) were related to concurrent mean daily streamflows for three nearby continuous-record stations to estimate the long-term mean annual ground-water discharges at the partial-record sites. Streamflow measurements were made several days after no precipitation and represent base-flow conditions. The long-term mean annual ground-water discharge estimate from Baker Brook was used in model calibration, and the Parris and Roaring Brook ground-water-discharge estimates were used as inputs at the model edge. The Maintenance of Variance Extension, Type 1 (MOVE.1) method developed by Hirsch (1982) was used to provide an equation that relates ground-water discharge at the partial-record sites to that at the long-term stations. Mean annual ground-water discharge calculated at the continuous stations by the hydrograph-separation method PART (Rutledge, 1998) was entered into the equation to determine the long-term mean annual ground-water discharges at the partial-record sites. The associated mean square error for each relation was used to combine the multiple estimates for each partial-record site into weighted-average estimates of mean annual ground-water discharge to obtain the single best estimate. Information about the analysis for each partial-record site is summarized in table 8. The mean annual ground-water discharge estimate for Baker Brook at the contact was 1.60 ft$^3$/s.

## Ground-Water-Flow Model

The ground-water-flow model for the Richmond study site was designed to simulate long-term, steady-state ground-water levels, flow paths, and traveltimes. The model was calibrated to nonpumping conditions based on historical data and data collected during this study. A general calibration was first done for the model area, and then a detailed calibration was completed for that part of the model expected to be within the contributing area of the well field. Model characteristics, including hydraulic properties and recharge rates, are summarized in table 9.

**Table 8.** Summary of the long-term mean annual ground-water discharge analysis for partial-record sites, Richmond study site, Rhode Island.

[USGS, U.S. Geological Survey. USGS station number: Locations shown on figures 1 and 16; mi$^2$, square mile; ft$^3$/s, cubic feet per second]

| USGS station number | Station name | Drainage area (mi$^2$) | Number of measurements used in relation | Estimated long-term mean ground-water discharge (ft$^3$/s) | Streamflow-gaging stations used in relation | | Correlation coefficient |
|---|---|---|---|---|---|---|---|
| | | | | | USGS station number | Station name | |
| 01117840 | Parris Brook at Blitzkrieg Trail near Arcadia, R.I. | 7.18 | 17 | 9.15 | 01117468 | Beaver River near Usquepaug, R.I. | 0.85 |
| | | | | | 01117800 | Wood River near Arcadia, R.I. | .93 |
| | | | | | 01118300 | Pendleton Hill Brook near Clarks Falls, Conn. | .96 |
| 01117860 | Roaring Brook at Arcadia, R.I. | 5.01 | 16 | 9.50 | 01117468 | Beaver River near Usquepaug, R.I. | .85 |
| | | | | | 01117800 | Wood River near Arcadia, R.I. | .88 |
| | | | | | 01118300 | Pendleton Hill Brook near Clarks Falls, Conn. | .83 |
| 01117872 | Baker Brook at KG Ranch Road near Hope Valley, R.I. | 1.25 | 10 | 1.60 | 01117468 | Beaver River near Usquepaug, R.I. | .96 |
| | | | | | 01117800 | Wood River near Arcadia, R.I. | .98 |
| | | | | | 01118300 | Pendleton Hill Brook near Clarks Falls, Conn. | .96 |

## Model Design

Ground-water flow in the surficial deposits and the underlying bedrock was represented by a three-layered numerical model with a uniformly spaced grid. The numerical model was calibrated to 28 ground-water altitudes measured in the stratified deposits during February and March 1981 and December 1982 (Dickerman and others, 1989; Dickerman and Bell, 1993) near average ground-water and streamflow conditions and to two additional ground-water altitudes measured under near-average hydrologic conditions at the well field during this study on July 6, 2005. The July measurements were made 24 hours after minimal pumping at the well field. The model was calibrated to a generally shallow water table that approximates the land-surface topography in the till uplands. Ground-water levels in the uplands indicate a shallow water table averaging 16 ft below land surface in the USGS Hope Valley quadrangle (Bierschenk and Hahn, 1959). In addition to the ground-water altitudes, the long-term average ground-water discharge computed for Baker Brook at the valley-upland contact and streamflow loss as Baker Brook crosses the valley to the Wood River were used in model calibration. The loss determined for Baker Brook as it crosses the valley was also applied to a nearby unnamed tributary north of Baker Brook.

The ground-water-flow model subdivided the study area of 13.1 mi$^2$ into 283 rows and 207 columns and included a total of 109,551 active cells. Each cell was 100 by 100 ft square. The boundary of the model coincided with streams, ponds, or watershed divides (fig. 18). The large extent of the model minimized the effects of these boundaries on the contributing-area results.

Vertical discretization of the three-layered model was based on lithology and production well-screen placements. The top two layers were simulated as water-table layers (convertible layers), which allow a model cell in an underlying layer to become a water-table layer if the cell above becomes dry. The bottom layer was simulated by using a fixed transmissivity. Layer 1, the top layer, represented stratified deposits in the valley and till and shallow bedrock in the uplands. In

**Table 9.** Summary of simulated values for hydraulic properties and recharge rates in the ground-water-flow model for the Richmond study site, Rhode Island.

| Characteristics | Simulated values |
|---|---|
| | Hydraulic conductivity (feet per day) |
| Stratified deposits | Sand and gravel: generally 200, ranged from 100–400 |
| | Sand: generally 100, ranged from 40–50 near edges of valley |
| | Fine sand and silt: 50 |
| | Remaining sediments not subdivided: 80 in Wood River Valley and 100 in Brushy Brook Valley |
| Till and shallow bedrock | Generally 2, ranged from 0.5–6 |
| Bedrock | .05 |
| Ponds | Ranged from 50 in uplands to 5,000 in valley |
| | Ratio of horizontal to vertical hydraulic conductivity |
| Stratified deposits | 10:1 |
| Till | 10:1 |
| Bedrock | 1:1 |
| | Streambed vertical hydraulic conductivity (feet per day) |
| Bed sediments | 1 |
| | Porosity |
| Stratified deposits | 0.35 |
| Till | .35 |
| Bedrock | .02 |
| | Recharge rates (inches per year) |
| Stratified deposits | 29 |
| Upland hillslopes | 29 |
| Upland watersheds | 20 |
| Valley-fill wetlands | 22 |

the valleys, the bottom altitude of layer 1 was set at 65 ft or higher where it forms the geologic contact between stratified deposits and bedrock. The bottom of layer 1 was 50 ft below land surface in the uplands and near the edges of the valley where saturated stratified deposits are less than 10 ft thick; a relatively thick layer was used to increase numerical stability of the model. Layer 2, the middle layer, represented stratified deposits in the valley and bedrock in the uplands; layer 2 also included the production-well screens. The bottom altitude of layer 2 represented the bedrock surface in the valley at altitudes less than 65 ft and 100 ft below land surface in the uplands. Layer 3, the bottom layer, represented only bedrock. The bottom altitude of layer 3 is 200 ft below land surface in the uplands or the bedrock surface in the valley; thus, the total thickness of till and bedrock was assigned a constant value of 200 ft throughout the model.

The interaction between surface water and ground water was simulated as a head-dependent flux boundary in layer 1 primarily by using the stream-routing package (Prudic, 1989) developed for MODFLOW (fig. 18). The stream-routing package accounts for gains and losses of water in each stream cell and routes flow from upstream to downstream. Streams that flow in and out of ponds and lakes were simulated as flowing through these surface-water bodies. Ground-water discharges entering the model from areas not directly simulated were specified at the first boundary stream cell. Ground-water discharges were specified either by the long-term estimates based on the partial-record sites (table 8) or by areal estimates determined from the Wood River streamflow-gaging stations (table 7). The model contained 1,693 stream cells.

During model calibration the MODFLOW drain package (Harbaugh and others, 2000) was also used to simulate a head-dependent flux boundary where a small stream from the 1:5,000 stream coverage drains an upland watershed adjacent to Baker Brook watershed and flows into Browning Mill Pond (fig. 18). Inclusion of this stream allowed for a more accurate representation of ground-water levels and flow patterns in the area. This stream was simulated with 46 drain cells.

Surface-water altitudes for the head-dependent flux boundary were interpolated from topographical contours

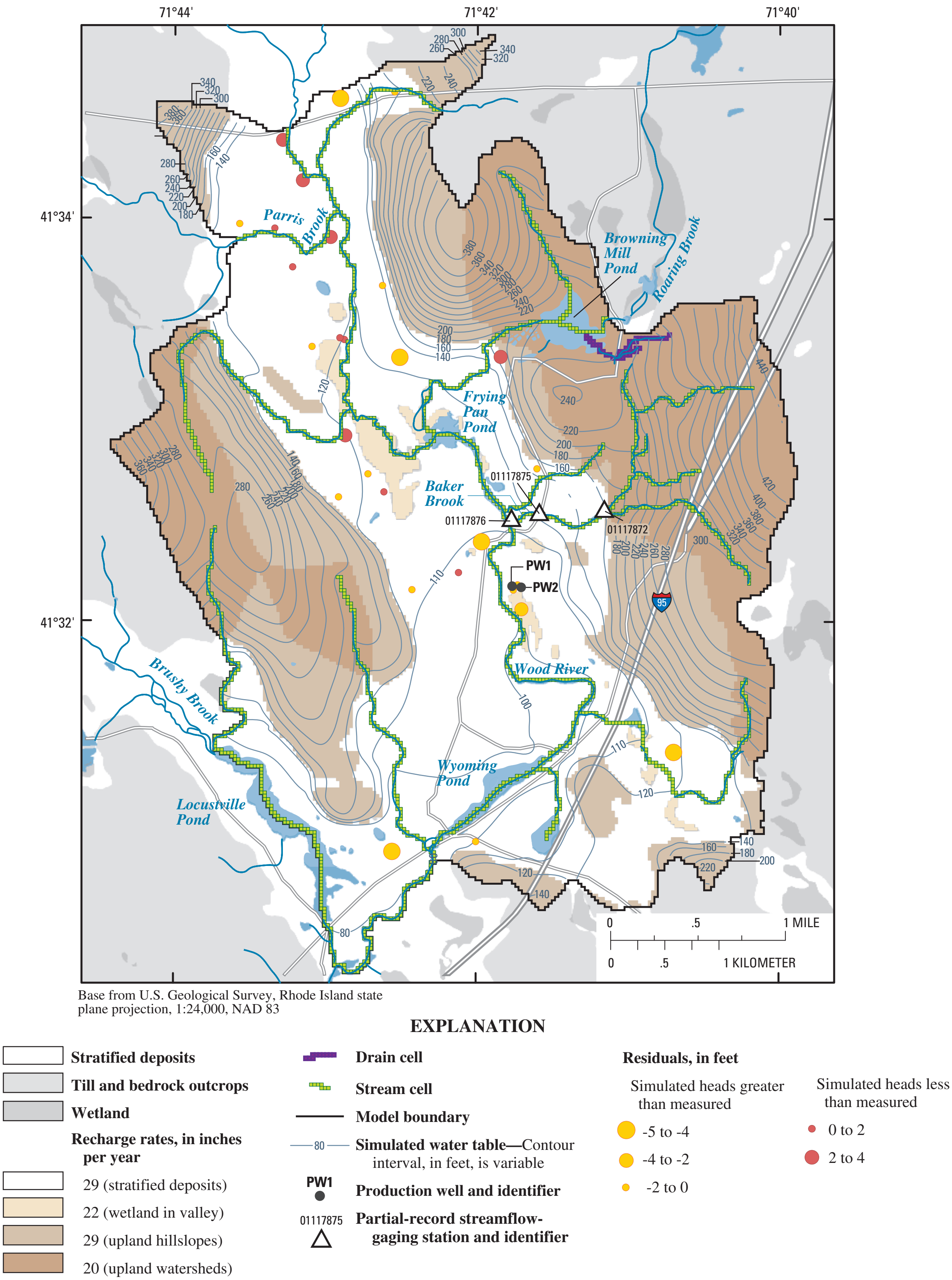



**Figure 18.** Model-boundary types, recharge rates, simulated water-table contours for nonpumping, steady-state conditions, and spatial distribution of residuals (measured-simulated), Richmond study site, Rhode Island.

intersecting streams and from pond altitudes shown on the USGS Hope Valley quadrangle. In addition, the stage of the Wood River measured at the well-field site on July 6, 2005, and 17 stage measurements reported by Dickerman and others (1989) and Dickerman and Bell (1993) at several sites including Baker Brook and additional sites for the Wood River were used. Both water depth and bed thickness were set equal to 1 ft so that the top and bottom bed altitude could be determined from surface-water altitudes. Tributary streams were simulated as 3 to 10 ft wide and the Wood River was simulated as 40 and 50 ft wide. A vertical hydraulic conductivity of 1 ft/d was used to represent bed sediments because most streams in the study area are fast-moving over coarse-grained sediments. Streambed conductances simulated in the model ranged from 300 $ft^2/d$ for the narrow tributaries to 5,000 $ft^2/d$ for the Wood River.

Effective recharge rates, which account for ground-water evapotranspiration, were distributed based on surficial geology and hydrography (fig. 18). A recharge rate of 29 in/yr based on long-term averages at the Wood River streamflow-gaging stations was applied to the stratified deposits. Because the study area is generally rural, overland runoff is considered minimal in areas underlain by these deposits. The same recharge rate, 29 in/yr, was applied to upland hillslopes that drain toward the valley and have no streams or water bodies at their base. This rate accounts for both ground-water and surface-water runoff from the hillslopes that recharges the stratified deposits at and near the valley-upland contact. A recharge rate of 20 in/yr was applied to upland watersheds. This rate is less than the basin-wide average ground-water discharge (effective recharge) determined for the Wood River streamflow-gaging stations, about the same as the rate determined for Pendleton Hill Brook station, which drains a predominately upland watershed, and within the reported range of recharge rates determined for till-dominated watersheds by computerized hydrograph-separation methods.

Evapotranspiration rates in wetlands are poorly defined. Some studies have indicated that evapotranspiration rates from wetlands are higher and other studies that the rates are lower than evaporation rates from open-water bodies (Mitsch and Gosselink, 1993). For this study, an average evapotranspiration rate equivalent to evaporation from a shallow, open water surface was assumed to represent the wetlands in the valley adequately. A specified flux of 22 in/yr was applied to wetland areas by subtracting the evaporation rate from a free-water surface (29 in/yr) (Farnsworth and others, 1982) from the rate of precipitation for southern Rhode Island (51 in/yr). Conceptually, some of this water may infiltrate, particularly under pumping conditions, or move across the wetland as overland flow. The specified flux applied in upland wetlands was the same as recharge applied to the surrounding materials.

Hydraulic conductivity values were assigned on the basis of lithology. For the valley fill, the surficial materials map (fig. 16) and the geologic sections (fig. 17) provided a general framework for distributing hydraulic conductivity for the depositional sequence that includes the sequences at (Wood River valley sequence 3) and immediately north (Wood River valley sequence 4) of the production well field. The remaining stratified deposits in the Wood River valley were simulated with one value, as were the stratified deposits in Brushy Brook valley. Final calibrated hydraulic conductivity values for the sand and gravel deposits were generally 200 ft/d, but were as high as 400 ft/d for the sand and gravel deposits at the well field. Final values were generally 100 ft/d for sand and 50 ft/d for fine sand and silt. Final hydraulic conductivity values for upland till and shallow bedrock were generally 2 ft/d, but values ranged from 0.5–6 ft/d. Bedrock was assigned a value of 0.05 ft/d, and this value was not changed during model calibration. Ponds completely contained within the model were assigned high hydraulic conductivity values in comparison to surrounding materials to simulate minimal resistance to flow and the corresponding flat gradient across these water bodies. Final hydraulic conductivity values for the lithologic units and ponds are summarized in table 9.

## Simulation of Ground-Water Flow

The altitude and configuration of the simulated water table for long-term, nonpumping, steady-state conditions are shown in figure 18 at 20-ft contour intervals except for a 10-ft interval in the valley that includes the well-field area. The simulated water-table contours and flow directions are consistent with the conceptual model of ground-water flow in the study area. Ground water flows from topographically high areas and discharges to streams and ponds. In the uplands, the water table approximately parallels the land surface and simulated ground-water divides generally coincide with watershed divides. The water-table gradient is steepest in the till uplands and stratified deposits near the contact and flattens in the more transmissive valley-fill areas.

Simulated ground-water flow in the stratified deposits is nearly perpendicular to the main valley streams, Wood River and Brushy Brook, except in areas where flow paths are affected by large ponds formed by dams, such as Frying Pan Pond north of the well-field site. Ground-water flow is nearly parallel to most of the small tributaries in the valley, which are minimally gaining or losing as they flow over transmissive stratified deposits. These ground-water-flow patterns are consistent with those shown on a water-table map for the stratified deposits drawn by Dickerman and Bell (1993).

The relation between simulated and measured ground-water altitudes in the stratified deposits indicates a reasonable agreement (fig. 19A). The mean absolute residual is 2.0 ft, which is less than 2 percent of the total difference in ground-water altitude, 112.7 ft, measured at the observation wells. A comparison of residuals indicates that the differences between simulated and measured water levels are generally randomly distributed around zero (fig. 19B). Simulated heads in some cases exceed measured heads (negative residuals) at low altitudes. These negative residuals are in areas that have steep hydraulic gradients near dams, where water levels are difficult to match, or near wetlands, which can reduce heads in

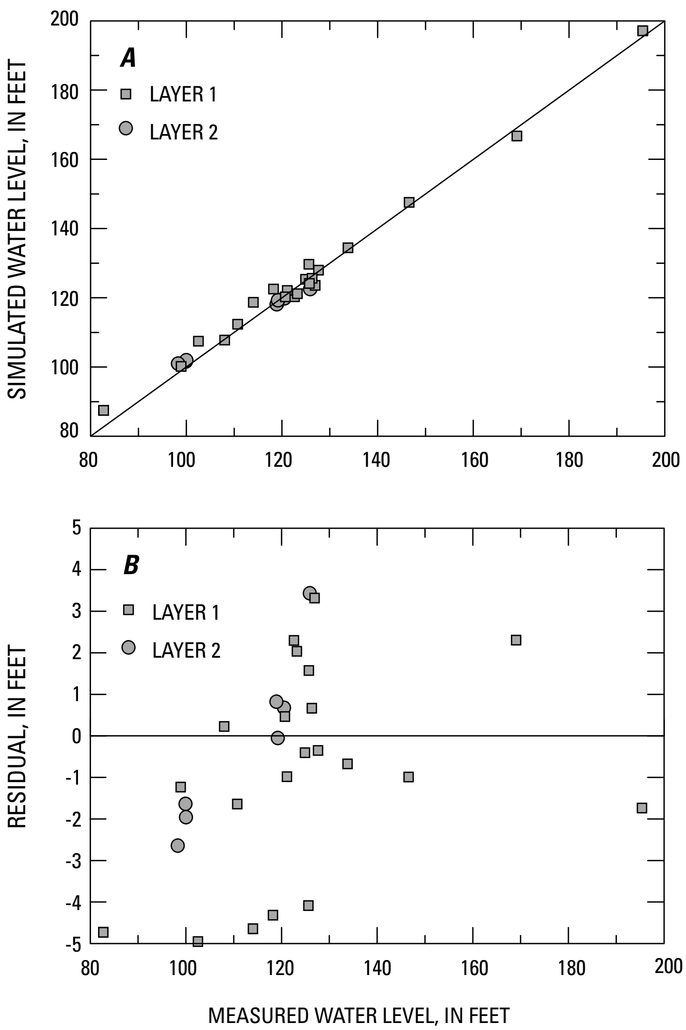



**Figure 19.** (*A*) Relation between simulated and measured ground-water levels and (*B*) residual (measured minus simulated) ground-water levels as a function of measured ground-water levels, Richmond study site, Rhode Island.

adjacent areas. Residuals in the remainder of the model show no discernible spatial trends (fig. 18).

Simulated streamflows also compared favorably with the long-term average ground-water discharge calculated for Baker Brook at the valley-upland contact and with streamflow loss measured downstream of this contact. Simulated streamflow at the contact was 1.62 $ft^3/s$ or 0.02 $ft^3/s$ more than the long-term average ground-water discharge at this site. Net simulated streamflow loss between the contact and the partial-record site 2,300 ft downstream was 0.09 $ft^3/s$ compared to 0.12 $ft^3/s$ for the measured value, and simulated net loss between the contact and the Wood River was 0.14 $ft^3/s$ compared to the estimated loss of 0.17 $ft^3/s$. Baker Brook, however, simulates as gaining flow for parts of the brook (7 of 42 stream cells) as it flows over the stratified deposits. The total simulated streamflow loss between the contact and the partial-record site and between the contact and the Wood River was 0.13 $ft^3/s$ and 0.19 $ft^3/s$.

The simulated long-term nonpumping, steady-state ground-water budget for the study area (table 10) indicates that precipitation recharge provides 89 percent of the total inflow. Conceptually this percentage represents both direct infiltration of precipitation and surface runoff from upland hillslopes that recharges the valley near the contact. Streamflow loss from natural infiltration accounts for 11 percent of the total inflow; most of this streamflow loss is from tributaries where they flow over the stratified deposits and at the downgradient areas of the ponds. Ground water discharges through the streams and ponds. The simulated water budget for the stratified deposits only (table 10) indicates that precipitation recharge directly on the stratified deposits accounts for 58 percent of the inflow, but upland sources contribute a significant amount (42 percent). These upland sources include lateral and vertical flow from till and bedrock (30 percent) and streamflow loss from tributary streams (12 percent).

**Table 10.** Simulated steady-state average annual hydrologic budget for nonpumping conditions, Richmond study site, Rhode Island.

[$ft^3/s$, cubic feet per second]

| Hydrologic budget component | Flow rate ($ft^3/s$) |
|---|---|
| **Modeled area** | |
| **Inflow** | |
| Recharge | 25.5 |
| Streamflow loss | 3.0 |
| Total inflow | 28.5 |
| **Outflow** | |
| Streamflow | 28.5 |
| Total outflow | 28.5 |
| **Glacial stratified deposits only** | |
| **Inflow** | |
| Recharge | 13.9 |
| Streamflow loss | 2.9 |
| From till | 6.5 |
| From bedrock | .5 |
| Total inflow | 23.8 |
| **Outflow** | |
| Streamflow | 23.6 |
| To till | .1 |
| To bedrock | .1 |
| Total outflow | 23.8 |

## Areas Contributing Recharge to Production Wells

Areas contributing recharge to the Richmond well field were determined on the basis of the calibrated steady-state model for simulated pumping conditions and tracking of pathlines with the MODPATH particle-tracking program. The locations and extents of the simulated areas contributing recharge to each production well pumping at one-half the maximum well-field withdrawal rate (337.5 gal/min) and the maximum well-field rate (675 gal/min) are illustrated in figures 20 and 21 respectively; the sizes of the areas and percentages of the total water withdrawn from each water source for the well field are listed in table 11.

The simulated areas contributing recharge for both well-field withdrawal rates extend northeastward from the well field to the uplands and include small isolated areas. The area contributing recharge to PW1 at both pumping rates also includes an isolated area remote from the well field on the opposite side of the Wood River northwest of the well field. The area contributing recharge to PW2 does not overlie the well for either pumping rate, but instead precipitation recharge in the vicinity of PW2 flows above and around its screened interval to PW1. The well field does not derive any of its water from nearby Wood River, even at the maximum pumping rate, because of the relatively large area upgradient of the well field and the resulting quantity of ground water that can be intercepted by the well field. The area contributing recharge, however, does underlie Baker Brook, which contributes water to the well field and indicates the importance of even small tributary streams distant from a well field.

The total area contributing recharge for the lower pumping rate is 0.31 $mi^2$. The well field derives most of its water from precipitation recharge; however, 15 percent of the withdrawn water is from Baker Brook as it flows from the upland-valley contact over the stratified deposits. PW1 derives a greater percentage of its water from surface-water infiltration than PW2. The area contributing recharge across the Wood River northwest of the well field is in an upland-till area near a ground-water divide. Particle tracks show that recharge originating in this till travels along deep ground-water-flow paths in the valley fill and, under pumping conditions, passes beneath the Wood River to PW1. Recharging water between this contributing area and the Wood River travels along shallow and intermediate-depth flow paths before discharging to the Wood River. At the higher pumping rate, the area contributing recharge (0.66 $mi^2$) extends farther up and down the valley to capture enough water to balance the pumping rate. The size of the contributing area beneath Baker Brook increases, and thus the quantity of surface water withdrawn by the well field increases; the percentage of water pumped from this water source (10 percent), however, is less than at the lower pumping rate. PW1 and PW2 derive approximately the same percentage of their water from streamflow loss. At the increased pumping rate, the area contributing recharge to the well field from across the Wood River includes both till uplands and stratified deposits near the contact.

**Table 11.** Sizes of areas contributing recharge to the Richmond production well field and the percentages of water withdrawn from different sources, Richmond study site, Rhode Island.

[gal/min, gallons per minute; $mi^2$, square mile]

| Model scenario | Size of area contributing recharge ($mi^2$) | Direct precipitation recharge and upland runoff (percent) | Infiltration of surface water (percent) |
|---|---|---|---|
| 337.5 gal/min | 0.31 | 85 | 15 |
| 675 gal/min | .66 | 90 | 10 |
| 675 gal/min and hydraulic conductivity of stratified deposits × 0.75 | .68 | 94 | 6 |
| 675 gal/min and hydraulic conductivity of stratified deposits × 1.25 | .64 | 87 | 13 |
| 675 gal/min and recharge rates × 0.75 | .85 | 86 | 14 |
| 675 gal/min and recharge rates × 1.25 | .54 | 93 | 7 |

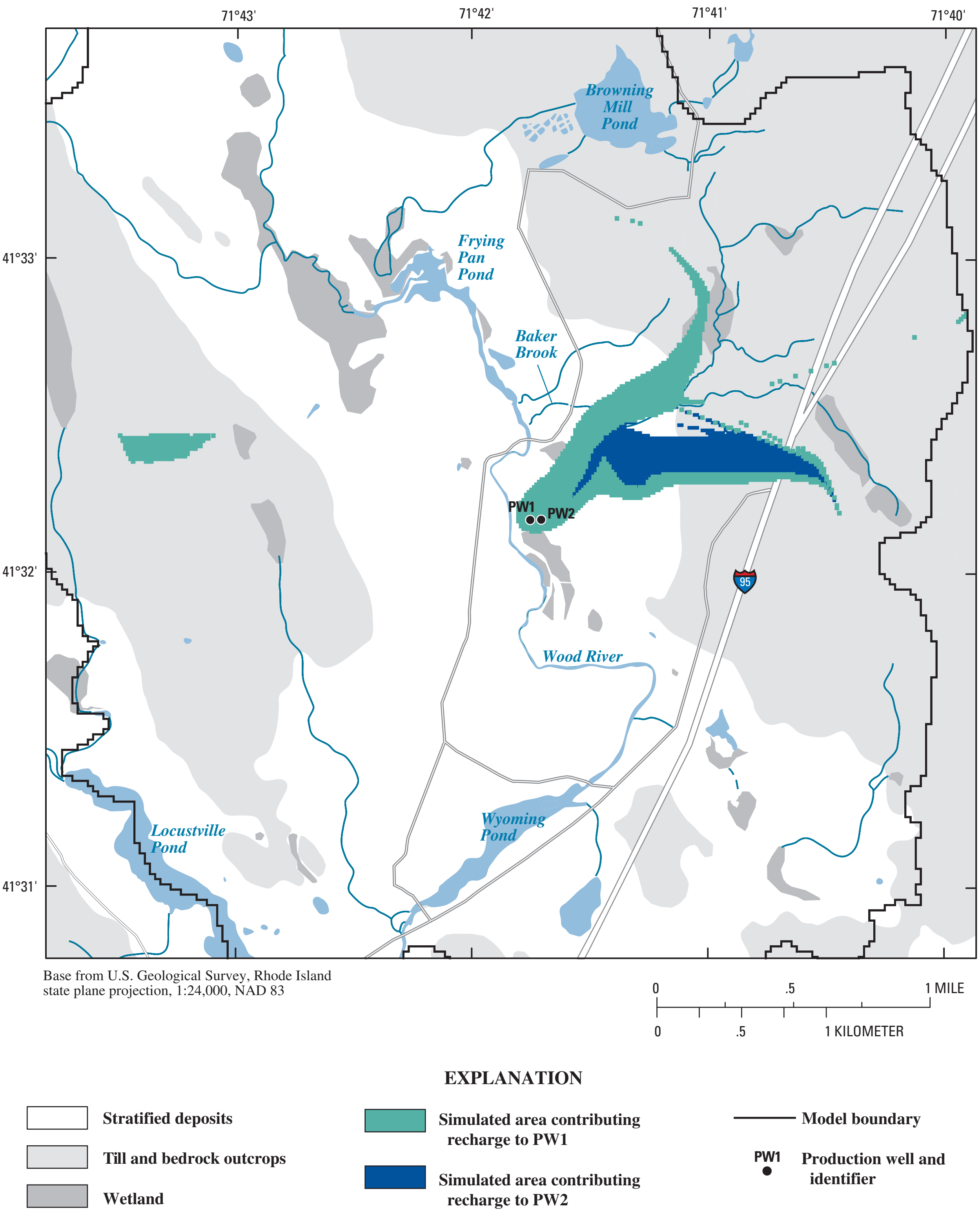



**Figure 20.** Simulated area contributing recharge to the Richmond well field at 337.5 gallons per minute, which is half of its maximum pumping rate of 675 gallons per minute, Richmond study site, Rhode Island.

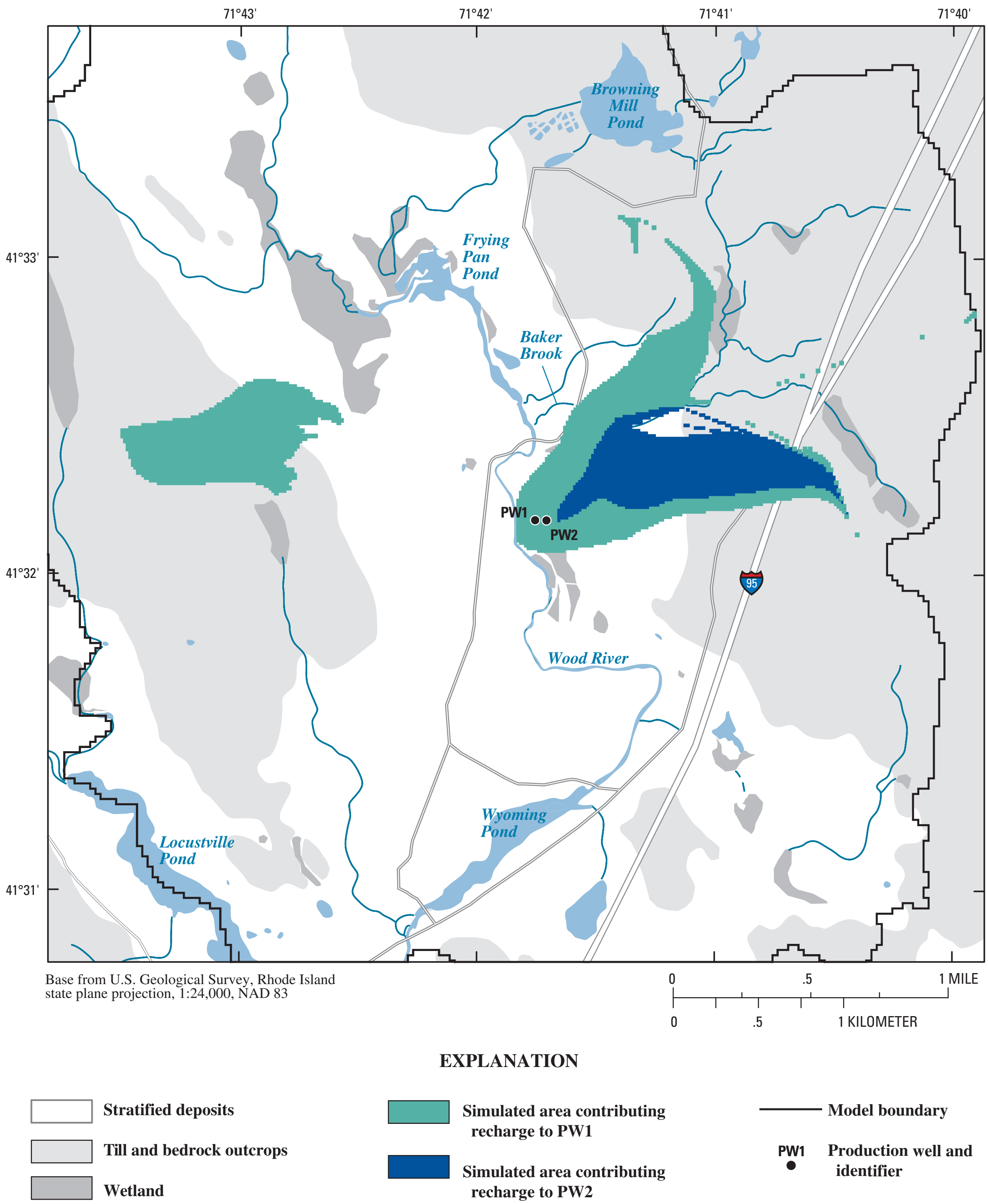



**Figure 21.** Simulated area contributing recharge to the Richmond well field at its maximum pumping rate of 675 gallons per minute, Richmond study site, Rhode Island.

Simulated traveltime estimates from recharging locations to the production wells for the maximum pumping rate, based on porosities of 0.35 for stratified deposits and till and 0.02 for bedrock, are shown in figure 22. Estimated traveltimes ranged from less than 1 year to more than 100 years; 54 percent of the traveltimes were 10 years or less, 83 percent were 20 years or less, and 98 percent were 50 years or less. Water that recharges the stratified deposits at the well field has the shortest traveltimes whereas water originating from recharge locations near upland ground-water divides has the longest traveltimes. The shortest ground-water traveltime from the area contributing recharge across the Wood River from the well field is about 9 years. A small area of till and exposed bedrock surrounded by stratified deposits northeast of the well field affects the pattern of traveltimes by increasing traveltimes at and upgradient of this till area.

## Sensitivity and Uncertainty Analysis

A sensitivity analysis of the effects of selected model-input values on the simulated areas contributing recharge and the sources of water to the well-field was done for the maximum pumping rate of 675 gal/min. Reasonable alternative values were chosen to provide insights into the importance of these values on the area contributing recharge to a well field adjacent to a river in a relatively broad valley-fill setting. This analysis provides a measure of the uncertainty associated with the contributing area size, shape, and location by comparison to the delineated contributing area.

The hydraulic connection between the Wood River and the underlying aquifer was reduced by one-half and increased by a factor of 2 by altering the vertical hydraulic conductivity of riverbed sediments between Frying Pan Pond and Wyoming Pond. This range of vertical hydraulic conductivity resulted in areas contributing recharge nearly identical to the delineated contributing area because flow paths were similar and river water was not induced. Even by increasing the vertical hydraulic conductivity between the river and the aquifer by an order of magnitude from 1 ft/d to 10 ft/d, the well field did not derive any of its water from induced infiltration of river water. Thus, even at the maximum rate and with surface and ground waters well connected, the well field derived its water from intercepted ground water because of the large upgradient area.

The hydraulic conductivity of stratified deposits was decreased and increased by 25 percent. The sizes of the areas contributing recharge to the well field and the percentages of water drawn from different sources were slightly different from those calculated by the base model (table 11), but the locations of the contributing areas were shifted either downvalley or upvalley (fig. 23). For the decreased hydraulic conductivity, the simulated ground-water flow direction in the stratified deposits was more nearly perpendicular to the valley axis and the Wood River. This change caused the contributing area to shift downvalley or southward. Increasing the hydraulic conductivity caused the opposite effect because the flow direction had a stronger downvalley component that resulted in an upvalley or northward shift in the contributing area. The shift in the area contributing recharge is most evident for the contributing area northwest of the well field because flow directions are affected more on the west side of the Wood River and because of the long distance from recharging locations to the well field. Because the decreased hydraulic conductivity also raised simulated ground-water levels in the stratified deposits above those calculated by the base model, less tributary streamflow loss occurs and less of the pumped water is derived from Baker Brook. The increased hydraulic conductivity has the opposite effects on ground-water levels and streamflow loss; the well field derives more streamflow from Baker Brook and, because of the stronger downvalley component of ground-water flow, from the tributary north of the brook. These small changes in the proportion of tributary streamflow withdrawn by the well field cause corresponding small change in contributing-area size (table 11), which is mostly reflected in the contributing area across the Wood River.

Additional sensitivity tests were done by decreasing and increasing long-term average annual recharge rates by 25 percent across the study area (table 11 and fig. 24). Because of the reduced recharge rates, the area contributing recharge to the well field expanded in almost all directions, increasing in size from 0.66 $mi^2$ to 0.85 $mi^2$. The percentage of pumped water from tributary loss also increased, from 10 to 14 percent, because the contributing area expanded beneath both Baker Brook and the stream north of the brook, simulated ground-water levels were lower than those calculated by the base model, and the quantity of tributary streamflow loss increased. The reduced recharge rate resulted in the largest simulated contributing area to the well field and the largest percentage from surface-water sources for the range of model-input values considered. Increasing the annual recharge rates by 25 percent caused the area contributing recharge to decrease to 0.54 $mi^2$ and the percentage from Baker Brook to decrease to 7 percent.

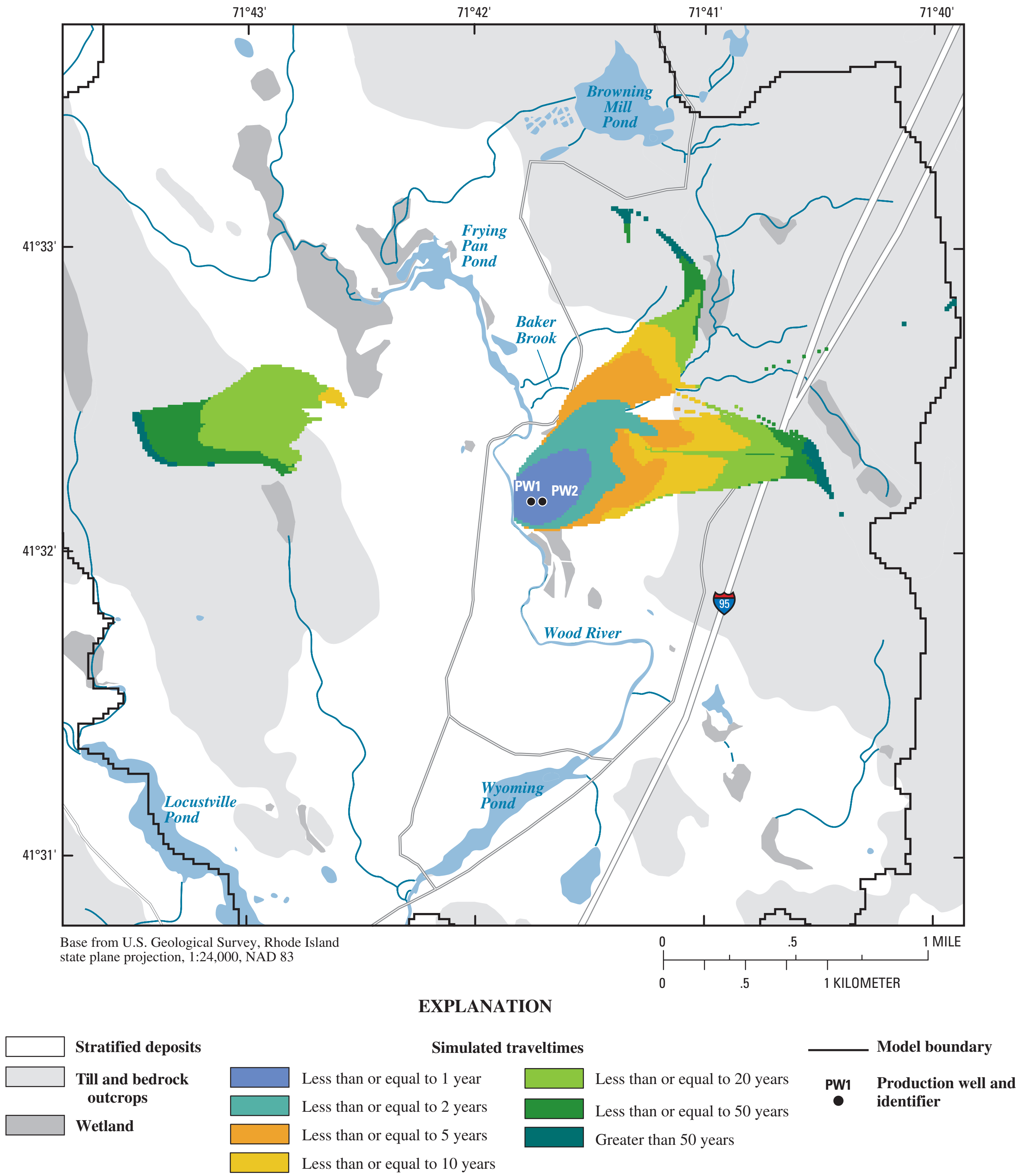



**Figure 22.** Simulated traveltimes to the Richmond well field at its maximum pumping rate of 675 gallons per minute, Richmond study site, Rhode Island.

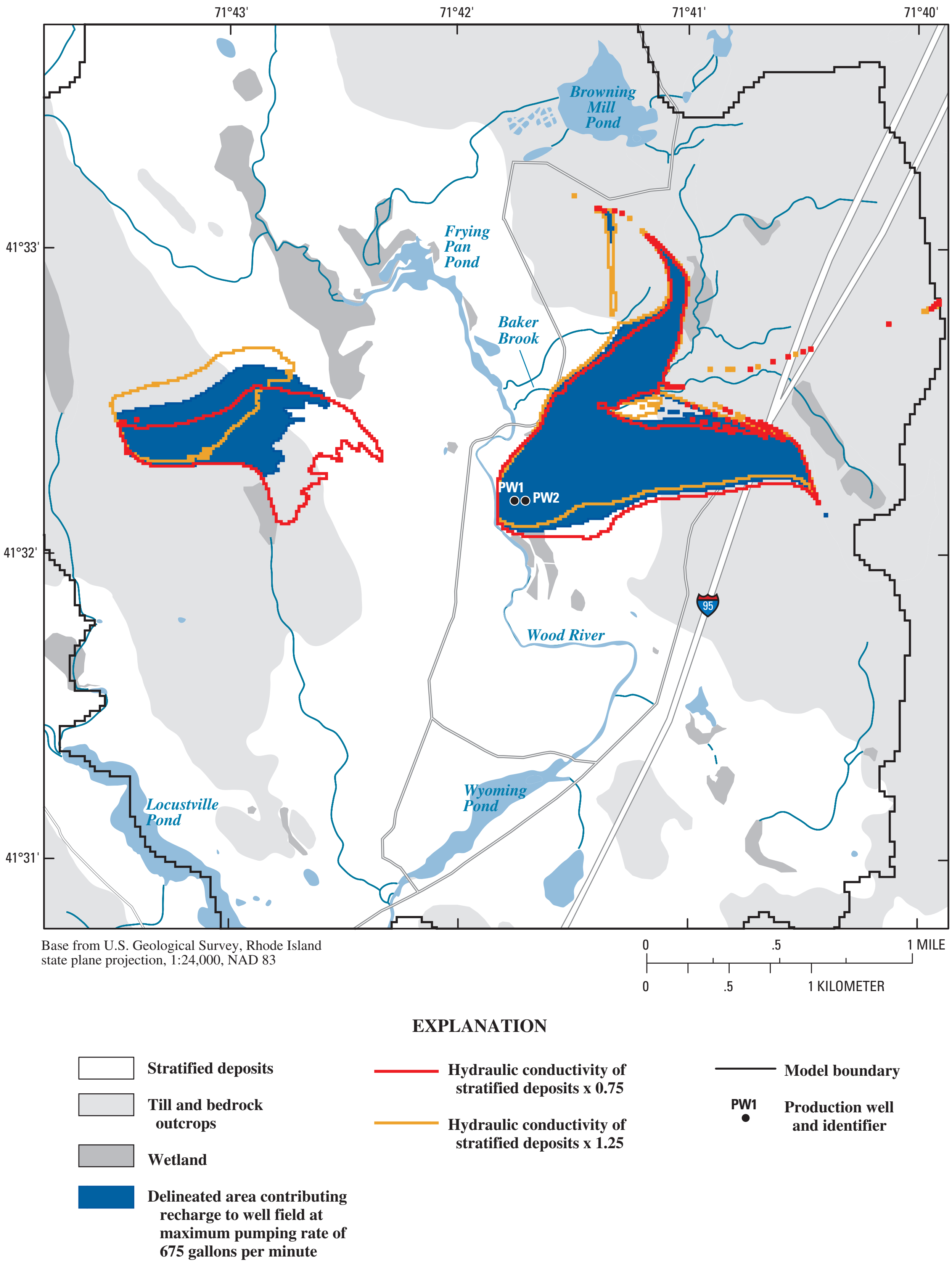



**Figure 23.** Sensitivity analysis of the effects of multiplying the hydraulic conductivity of stratified deposits by 0.75 and by 1.25, Richmond study site, Rhode Island.

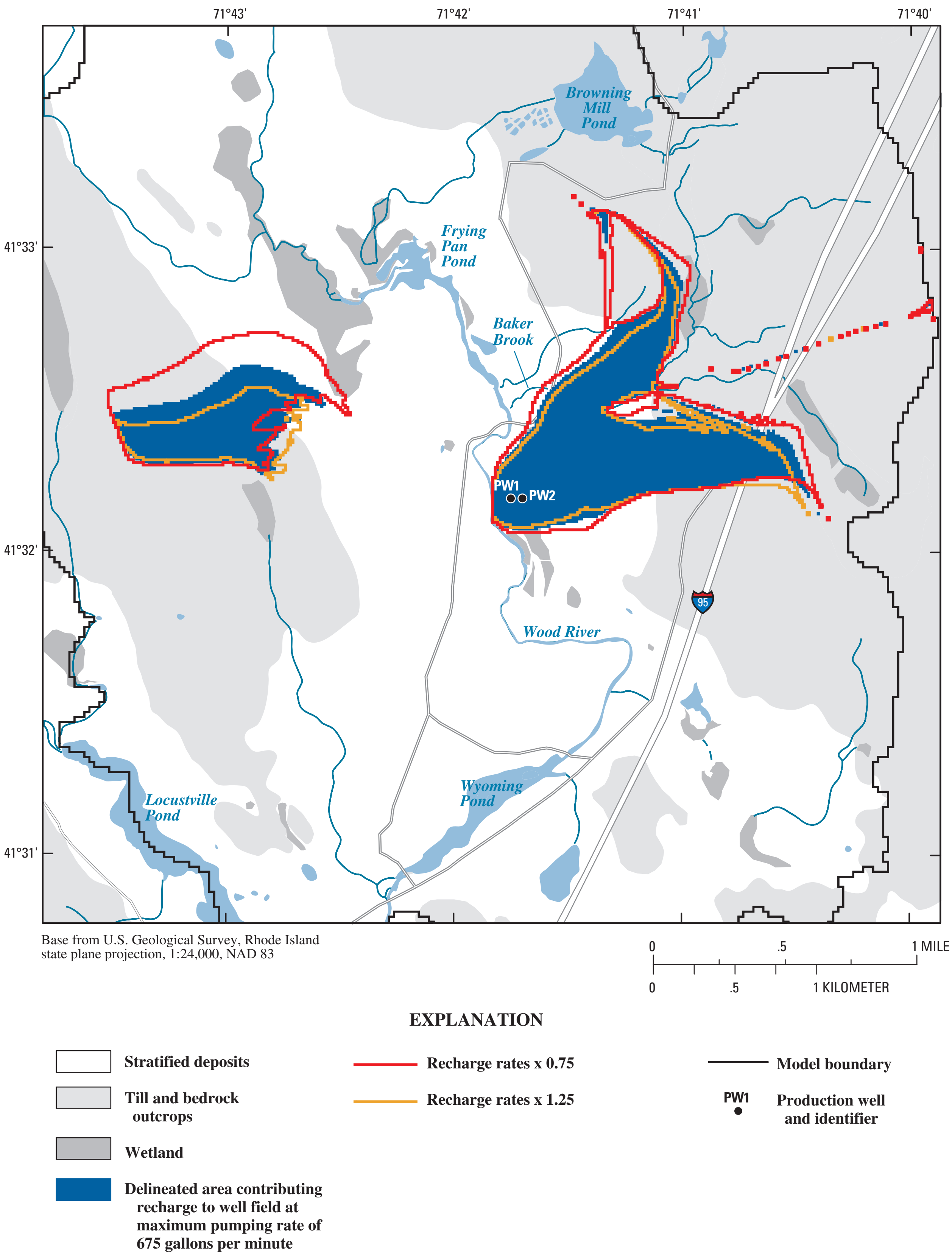



**Figure 24.** Sensitivity analysis of the effects of multiplying recharge rates by 0.75 and by 1.25, Richmond study site, Rhode Island.

# Summary and Conclusions

Areas contributing recharge and sources of water to production well fields in the Village of Harrisville, Town of Burrillville, and in the Town of Richmond, Rhode Island, were determined on the basis of numerical steady-state ground-water-flow models representing long-term average hydrologic conditions. The U.S. Geological Survey (USGS), in cooperation with the Rhode Island Department of Health, Office of Drinking Water Quality, began a 2-year investigation in 2004 to increase understanding of the geohydrology and of the important hydrologic factors required to accurately delineate areas contributing recharge to the production wells. The production wells are screened in sand and gravel sediments in contrasting glacial valley-fill settings near potential surface-water sources. Differences between the settings include aquifer thickness and width, the size of the area upgradient of the well field, and the size of nearby streams. The area contributing recharge to a well is defined as the surface area where water recharges the ground water and then flows toward and discharges to the well.

In Harrisville, the production well field is composed of three wells in a narrow (approximately 0.5-mi-wide) valley-fill setting on opposite sides of Batty Brook, a small intermittent stream that drains 0.64 mi$^2$ at its confluence with the Clear River. The areal distribution of glacial deposits determined from USGS field maps and analysis of aerial photographs indicated that stratified deposits generally were less extensive than previously published. The well field is screened in the ice-proximal part of a deltaic deposit composed of collapsed coarse sand and gravel; the aquifer is thin (30 ft) but transmissive at the well field. Paired measurements of ground-water and surface-water levels indicated the direction of flow between the brook and the aquifer was downward during pumping conditions, except during periods of high seasonal recharge rates and low pumping withdrawals. Mean daily streamflows measured upstream and downstream of the well field during 2004–2005 indicated that a net streamflow loss began near average hydrologic conditions and lasted until after major precipitation events in the fall; net loss during this period was about 10 to 20 percent of the 2005 average well-field pumping rate. Long-term mean annual streamflow upgradient of the well field is 0.54 ft$^3$/s for Batty Brook and 0.18 ft$^3$/s for an unnamed tributary to Batty Brook.

Ground-water flow at the Harrisville study site was simulated by a two-layer model representing surficial deposits and the underlying bedrock. The model was calibrated by using 53 ground-water levels and 2 streamflows. The simulated nonpumping, steady-state hydrologic budget for the stratified deposits indicated that 62 percent of the inflow was from direct infiltration of precipitation and about 38 percent could be attributed to upland sources, either by infiltration from tributary streams (12 percent) or lateral and vertical flow from till and bedrock (26 percent).

The simulated area contributing recharge for the 2005 average Harrisville well-field pumping rate of 224 gal/min extended upgradient to ground-water divides in the uplands and covered 0.17 mi$^2$. The well field derived 62 percent of its water from intercepted ground water and 38 percent from infiltration from streams in Batty Brook watershed. The shape of the contributing area and the source of water to an individual well were strongly affected by the other two pumping wells: the farthest upgradient well derived a greater percentage of its water from intercepted ground water, whereas the farthest downgradient well derived a greater percentage of its water from stream infiltration. For the maximum well-field pumping rate of 600 gal/min, the area contributing recharge expanded to 0.44 mi$^2$ and intercepted additional ground water and infiltration of stream water; the simulated percentage of water derived from surface water, however, was the same as for the average pumping rate. Because of the small size of the Batty Brook watershed, most of the precipitation recharge in the watershed was withdrawn by the well field at the maximum pumping rate either by intercepted ground water or indirectly by streamflow loss. In contrast to the simulation results for the average pumping rate, the farthest downgradient well derived a greater percentage of its water by capturing ground water that normally would have discharged to the Clear River and its tributaries, and the middle well derived the greater percentage of water from the stream. Because the production wells are screened in a thin and transmissive aquifer in a small watershed, simulated ground-water traveltimes from recharge locations to the discharging wells were relatively short: 93 percent of the traveltimes were 10 years or less.

Results of a sensitivity analysis of the area contributing recharge to the well field at its maximum pumping rate indicated that the size of the contributing area changed the most when the recharge rate and the hydraulic connection between streams and aquifer were changed. Reducing the recharge rate by 25 percent and the connection between streams and the aquifer by 50 percent resulted in the largest contributing areas for the range of model-input values considered; the areas contributing recharge included an area on the opposite side of the Clear River from the well field. At the reduced recharge rate, a small amount of pumped water (less than 1 percent) was from the Clear River itself.

In Richmond, a production well field in a moderately broad (approximately 1.2-mi-wide) valley-fill setting is composed of two wells adjacent to and east of the Wood River. The wells are screened in the coarse-grained ice-proximal part of a morphosequence with saturated thickness greater than 60 ft. Streamflow measured in Baker Brook, a tributary to the Wood River 0.4 mi. north of the well-field site, indicated that the natural net streamflow loss between the upland-valley contact and a site 2,300 ft downstream is 0.12 ft$^3$/s at average hydrologic conditions. Long-term mean annual ground-water discharge at the upland-valley contact is 1.60 $ft^3/s$.

Ground-water flow was simulated at the Richmond study site by a three-layer model representing surficial deposits and bedrock. The model was calibrated by using 28 ground-water levels and 1 streamflow. The simulated nonpumping, steady-state water budget for the stratified deposits indicated that 58 percent of the inflow was from direct recharge from precipitation and 42 percent could be attributed to upland sources, including infiltration from tributaries (12 percent) and runoff from till and bedrock (30 percent).

Simulated areas contributing recharge for the maximum Richmond well-field pumping rate of 675 gal/min and for one-half the maximum rate extended northeastward from the well field to ground-water divides in the uplands. The area contributing recharge also included a remote, isolated area on the opposite side of the Wood River from the well field. The area contributing recharge to the upgradient well did not include the area above it; instead, recharge in the vicinity of the well flows above and around its screen to the other well. Model simulations indicated that the well field did not derive any of its water from the Wood River, even when the hydraulic connection between the river and aquifer was increased by an order of magnitude, because of the large watershed and associated quantity of ground water that can be captured by the well field.

The area contributing recharge for one-half the maximum rate was 0.31 $mi^2$, and the well field derived most of its water from precipitation recharge; however, 15 percent was loss from Baker Brook, indicating the importance of even small, distant tributary streams to the contributing area to a well. The small area contributing recharge to the well field on the opposite side of the Wood River is in the till uplands. For the maximum well-field rate, the 0.66-$mi^2$ area contributing recharge extended farther up and down the valley to intercept additional ground water and infiltration from Baker Brook; the percentage of pumped water derived from the brook (10 percent), however, was less than for the lower pumping rate. The area contributing recharge across the Wood River included upland till and stratified deposits near the upland-valley contact. Because the Richmond well field is in a larger watershed with saturated sediments thicker than at the Harrisville site, the overall ground-water traveltimes are greater: 54 percent of the traveltimes are 10 years or less, 83 percent are 20 years or less, and 98 percent are 50 years or less. The shortest traveltime from the area contributing recharge across the Wood River from the well field was 9 years.

A sensitivity analysis of the area contributing recharge to the well field when pumped at 675 gal/min indicated that the size of the contributing area changed the most when the recharge rate was modified. Reducing the recharge rate by 25 percent resulted in the largest contributing area and included infiltration from Baker Brook and a second tributary stream that drains the uplands. When the hydraulic conductivity of the stratified deposits was varied by 25 percent, the size of the area contributing recharge did not change but the location shifted either up or down the valley. By increasing the hydraulic conductivity by 25 percent, the ground-water-flow direction had a stronger downvalley component that resulted in an upvalley shift in the contributing area and infiltration from the second tributary stream. The shift in the location of the area contributing recharge was most evident for the remote contributing area across the Wood River because of the long distance from recharge locations to the well field.

Recharge rate was the hydrologic factor that most affected the sizes of the areas contributing recharge to the production wells in both valley-fill settings. The locations of the areas contributing recharge in both settings were affected by the recharge rates, aquifer transmissivities, and the locations of upgradient ground-water divides. Depending on the setting and the pumping rate, a nearby surface-water body may also be a major factor affecting the size and location of the contributing area to a well. For a setting similar to the Harrisville study site, which has a small watershed area upgradient of the well field and a corresponding limited quantity of ground water that could be intercepted by the well, the quantity of surface water and the hydraulic connection between the surface water and the aquifer are important factors for determining the contributing area to a well. In a setting such as the Richmond study site, which has a large area upgradient of the well field, a well near a surface-water body may not always draw surface water, even when surface and ground waters are well connected; the amount of water that the well may draw from surface water can also depend on the pumping rate and the quantity of ground water that can be intercepted by the well. The area contributing recharge to a well also may include areas on the opposite side of a river, even with this major source of water in close proximity to the well; precipitation recharge originating on the opposite side of the river may pass beneath the river under pumping conditions and discharge to the well instead of, or including, induced infiltration of river water.

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