

# **Hydrogeologic Setting and Ground-Water Flow Simulations of the Pomperaug River Basin Regional Study Area, Connecticut**

By Forest P. Lyford, Carl S. Carlson, Craig J. Brown, and J. Jeffrey Starn

Section 6 of

**Hydrogeologic Settings and Ground-Water Flow Simulations for Regional Studies of the Transport of Anthropogenic and Natural Contaminants to Public-Supply Wells—Studies Begun in 2001**

Edited by Suzanne S. Paschke

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# Hydrogeologic Setting and Ground-Water Flow Simulations of the Pomperaug River Basin Regional Study Area, Connecticut

By Forest P. Lyford, Carl S. Carlson, Craig J. Brown, and J. Jeffrey Starn

## Abstract

The transport of anthropogenic and natural contaminants to public-supply wells was evaluated for the glacially derived valley-fill aquifer in the Pomperaug River Basin, Connecticut, as part of the U.S. Geological Survey National Water-Quality Assessment Program. The glacial valley-fill aquifer in the Pomperaug River Basin regional study area is representative of the glacial aquifer system in the Northeastern United States, is used extensively for public water supply, and is susceptible and vulnerable to contamination. A two-layer, steady-state ground-water flow model of the study area was developed and calibrated to average conditions for the period from 1997 to 2001. The calibrated model and advective particle-tracking simulations were used to compute areas contributing recharge and traveltimes from recharge areas for selected public-supply wells. Model results indicate areal recharge provides approximately 87 percent of the ground-water inflow and streams provide approximately 13 percent of ground-water inflow. Ground-water discharge from the model area is to streams (96 percent) and wells (4 percent). Particle-tracking results indicate traveltimes from recharge areas to wells range from less than 1 year to more than 275 years, the median traveltime to wells range from 0.2 to 25 years. Approximately 73 percent of the traveltimes are less than 10 years indicating water quality in the glacial valley-fill aquifer is susceptible to the effects of overlying land use.

## Introduction

The Pomperaug River Basin regional study area for the transport of anthropogenic and natural contaminants to public-supply wells (TANC) study is located in the northeast glacial aquifer system (Warner and Arnold, 2005) within the Connecticut, Housatonic, and Thames River Basins study unit of the U.S. Geological Survey National Water-Quality Assessment (NAWQA) program (fig. 6.1).

## Purpose and Scope

The purpose of this Professional Paper section is to present the hydrogeologic setting of the Pomperaug River Basin regional study area. The section also documents the setup and calibration of a steady-state regional ground-water flow model for the study area. Ground-water flow characteristics, pumping-well information, and water-quality data were compiled from existing data to develop a conceptual understanding of ground-water conditions in the study area. A two-layer steady-state ground-water flow model of the glacial aquifer of the Pomperaug River Basin was developed and calibrated to average conditions for the period from 1997 to 2001. The 5-year period 1997–2001 was selected for data compilation and modeling exercises for all TANC regional study areas to facilitate future comparisons between study areas. The ground-water flow model and associated particle tracking were used to simulate advective ground-water flow paths and to delineate areas contributing recharge to selected public-supply wells. Ground-water traveltimes from recharge to public-supply wells, oxidation-reduction (redox) conditions along flow paths, and presence of potential contaminant sources in areas contributing recharge were tabulated into a relational database as described in Section 1 of this Professional Paper. This section provides the foundation for future ground-water susceptibility and vulnerability analyses of the study area and comparisons among regional aquifer systems.

## Study Area Description

The Pomperaug River Basin regional study area encompasses the glacially derived, valley-fill aquifer of the Pomperaug River Basin. The study area was chosen because the aquifer is used extensively for public water supply, is susceptible and vulnerable to contamination, and is representative of the glacial aquifer system in the Northeastern United States. Characteristics of the Pomperaug River Basin aquifer system are similar to many valley-fill aquifer system in the Eastern

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Base from U.S. Geological Survey digital data, 1:2,000,000, 1972, Albers equal-area projection

EXPLANATION

- Pomeraug River Basin regional study area
- Glacial deposits aquifer—Darker areas represent sand, gravel, and valley-fill aquifers locally
- USGS NAWQA study unit—Connecticut, Housatonic, and Thames River Basins
- Southern limit of Pleistocene continental glaciation

Figure 6.1. Location of the Pomeraug River Basin regional study area within the glacial aquifer system.

Hills and Valley Fills hydrophysiographic region of Randall (2001), which encompasses much of the most populated parts of New England, northern New Jersey, and eastern New York within the glacial aquifer system (table 6.1).

## Topography and Hydrography

The Pomperaug River Basin regional study area covers about 128 km<sup>2</sup> of the Pomperaug River Basin in west-central Connecticut and includes parts of the towns of Southbury, Woodbury, Roxbury, Watertown, Bethlehem, and Middlebury (fig. 6.2). The upper part of the basin is drained by the Nonnewaug and Weekepeemee Rivers, which join in Woodbury to form the Pomperaug River. Most of the study area is in the Nonnewaug River and Pomperaug River drainage areas. Subbasins of the Pomperaug River Basin that are not in the study area are Transylvania Brook, East Spring Brook, and most of the Weekepeemee River (fig. 6.2). The major valleys trend north to south and are bounded on the east and west by till-covered bedrock uplands drained by numerous perennial streams. Streams in upland areas are oriented mostly from east to west on the east side and northwest to southeast on the north and west sides. Hesseky Brook flows northward through an area underlain by sand and gravel and joins the Pomperaug River near its origin at the confluence of the Nonnewaug and Weekepeemee Rivers. Manmade ponds are present on several tributary streams. Altitudes range from about 30 m near the confluence of the Pomperaug River with the Housatonic River to about 300 m at places on the basin divide.

Precipitation in the Pomperaug Basin averages about 117 cm/yr (Randall, 1996). Basin runoff measured in the Pomperaug River at Southbury, Connecticut, averaged 61 cm/yr during 1933–2001 (Morrison and others, 2002; table 1). The balance of about 56 cm/yr is lost mainly to evapotranspiration (Randall, 1996).

## Land Use

Land use in the Pomperaug River watershed has changed over the past 50 years from primarily undeveloped or agricultural lands to expanded residential, commercial, and light

industrial areas. Most residential areas are served by individual septic disposal systems (ISDS) and are characterized by low-density housing. Agricultural lands are located mostly within flood plains and produce silage corn, hay, and berries. Industrial uses are limited and include small, modern, high-tech industries. Upland areas are largely forested with scattered residences on 0.16-km<sup>2</sup> (40-acre) or larger lots.

## Water Use

Most water for public supply is obtained from wells completed in valley fill. Mazzaferro (1986a) estimated that as much as 33,300 m<sup>3</sup>/d could be withdrawn from valley-fill materials. Public-supply systems distribute water from wells completed in valley-fill deposits at six locations (fig. 6.2; table 6.2). Three of the locations (WF, WT, and HV) include several closely spaced wells, and two locations (UW1 and UW2) each include a single well. One condominium complex (WP) obtains water from a single well completed in valley fill, and four additional condominium complexes obtain water from wells completed in bedrock (fig. 6.2). Pumping rates at WF, UW1, UW2, HV, and WT wells (table 6.2) are based on several months to 5 years of measurements. Pumping rates for other wells are based on the population served, assuming a per-capita consumption of 0.38 m<sup>3</sup>/d. This rate is reasonable for household use (John Mullaney, U.S. Geological Survey, written commun., 2003) but may be somewhat higher than rates for condominium residents where grounds are not irrigated as heavily and for the NHS (Nonnewaug High School) and for the RM (Romatic Manufacturing Company) wells. Numerous residents in the valley and uplands obtain water from private wells for domestic uses, including lawn irrigation.

All of the water pumped from the WF wells and approximately 30 percent of the water pumped from the HV wells is transported out of the basin. Water pumped from other supply wells is used within the basin. Wastewater at the HV facility is treated in a wastewater-treatment plant south of the supply wells and then discharged to the Pomperaug River. Elsewhere, wastewater is disposed to ground water through private septic systems and local treatment facilities.

## 6-4 Hydrogeologic Settings and Ground-Water Flow Simulations for Regional TANC Studies Begun in 2001

**Table 6.1.** Summary of hydrogeologic and ground-water-quality characteristics for the glacial aquifer system and the Pomperaug River Basin regional study area, Connecticut.

[m, meters; cm/yr, centimeters per year; m<sup>3</sup>/s, cubic meters per second; m<sup>3</sup>/d, cubic meters per day; km, kilometers; Kh, horizontal hydraulic conductivity; Kz, vertical hydraulic conductivity; Sy, specific yield; n, porosity; mg/L, milligrams per liter]

Characteristic	Glacial aquifer system	Pomperaug River Basin regional study area
<b>Geography</b>		
Topography	Relief generally less than 300 m (Randall, 2001).	Relief approximately 300 m.
Climate	Precipitation 91 to 127 cm/yr; evapotranspiration 46 to 58 cm/yr (Randall, 1996).	Precipitation 117 cm/yr; evapotranspiration 53 to 56 cm/yr (Randall, 1996).
Surface-water hydrology	Runoff 41 to 76 cm/yr (Randall, 1996); streamflow varies widely with the size of drainage basin. Water-supply reservoirs and former mill ponds are common in upland and valley settings.	Runoff 61 cm/yr; flow in Pomperaug River at Southbury averages 71 m <sup>3</sup> /s (Morrison and others, 2002). Ponds and former water-supply reservoirs are present in uplands. A mill pond, largely silted, forms behind a dam on the Pomperaug River at Pomperaug.
Land use	Urban, suburban, rural residential, woodlands, farmland.	Suburban, rural residential, woodlands, farmland.
Water use	Potential aquifer yields generally less than 60,500 m <sup>3</sup> /d (Kontis and others, 2004).	Pumpage for public supply about 7,570 m <sup>3</sup> /d (this study). Potential aquifer yield of 33,300 m <sup>3</sup> /d (Mazzaferro, 1986a).
<b>Geology</b>		
Surficial geology	Glacially-derived sand and gravel in valleys that slope away from retreating ice sheets; limited fine-grained deposits; till prevalent in uplands but discontinuous under valley fill (Randall and others, 1988; Randall, 2001).	Mainly sand and gravel in a southward sloping valley (Stone and others, 1998); till covers uplands and underlies valley fill (Mazzaferro, 1986a).
Bedrock geology	Crystalline granitic and metamorphic rocks and sedimentary rocks; limited carbonate rocks (Randall, 2001; Randall and others, 1988).	Metamorphic crystalline rocks, granite, sedimentary rocks, and volcanics, mainly basalts.
<b>Ground-water hydrology</b>		
Aquifer conditions	Valley-fill aquifers that are generally less than 2.5 km wide and are unconfined; valley fill generally less than 67 m thick; depth to water generally less than 15 m. Streams that cross valley fill from upland areas are commonly sources of recharge; pumping near surface water commonly induces infiltration (Kontis and others, 2004).	A valley-fill aquifer that is generally less than 1.6 km wide and unconfined; valley fill generally less than 67 m thick; depth to water generally less than 15 m (Mazzaferro, 1986a; 1986b). Several tributary streams are likely sources of recharge. Pumping induces infiltration from streams in at least two areas.
Hydraulic properties	Valley fill: Kh= 1.5 to 150 m/d; Kh/Kz = 10:1 (commonly); n=0.3 to 0.4; Sy = 0.2 to 0.3 Till: Kh=0.003 to 3 m/d; Kh/Kz = 1; n=0.1 to 0.3; Sy = 0.04 to 0.28 Bedrock: Kh=0.003–0.3 m/d; Kh/Kz (limited information); n=0.005–0.02; Sy = 0.0001–0.005 (Randall and others, 1988; Bradbury and others, 1991; Melvin and others, 1992; Gburek and others, 1999).	Valley fill: Kh= 1.5 to 76 m/d; n=0.3 to 0.45. Till: Kh=0.003 to 3 m/d; n=0.2 to 0.3 Bedrock: K=0.003 to 1.5 m/d; n=0.005 to 0.02. Sy values not used for current study; Kh/Kz estimated at 1:1. (Mazzaferro, 1986a; Grady and Weaver, 1988; Starn and others, 2000).

**Table 6.1.** Summary of hydrogeologic and ground-water-quality characteristics for the glacial aquifer system and the Pomperaug River Basin regional study area, Connecticut.—Continued

[m, meters; cm/yr, centimeters per year; m<sup>3</sup>/s, cubic meters per second; m<sup>3</sup>/d, cubic meters per day; km, kilometers; Kh, horizontal hydraulic conductivity; Kz, vertical hydraulic conductivity; Sy, specific yield; n, porosity; mg/L, milligrams per liter]

Characteristic	Glacial aquifer system	Pomperaug River Basin regional study area
Ground-water hydrology—Continued		
Ground-water budget	Recharge to valley fill from infiltration of precipitation, 36 to 76 cm/yr. Recharge to valley fill from upland runoff often exceeds recharge from precipitation (Kontis and others, 2004; Morrissey and others, 1988). Pumpage generally less than 15 percent of water budget; most discharge is to streams (Morrissey, 1983; Tepper and others, 1990; Dickerman and others, 1990; Dickerman and others, 1997; Mullaney and Grady, 1997; Starn and others, 2000; Barlow and Dickerman, 2001; DeSimone and others, 2002.)	Recharge to valley fill from infiltration of precipitation, 48 to 61 cm/yr. Recharge to valley fill from upland runoff at least 50 percent of total recharge. Pumpage for public supply less than 5 percent of water budget; most ground water discharges to streams (Mazzaferro, 1986a; this study)
Ground-water quality		
	Dissolved solids less than 150 mg/L in crystalline-rock terrains and greater than 150 mg/L in sedimentary-rock terrains; pH, 6–8; oxic. Calcium and bicarbonate are the principal ions (Rogers, 1989). Redox conditions not defined regionally.	Dissolved solids generally less than 200 mg/L. Calcium and bicarbonate are the principal dissolved ions. Redox conditions are typically oxic in valley fill and suboxic to anoxic in bedrock (Grady and Weaver, 1988; this study).

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**Table 6.2.** Public-supply wells and pumping rates, Pomperaug River Basin regional study area, Connecticut.

[m, meters; m<sup>3</sup>/d, cubic meters per day]

Map name (fig. 2)	Well name	Number of wells	Depth or depth range (m)	Geologic unit (model layer in parenthesis)	Combined pumping rate (m <sup>3</sup> /d)	Basis for pumping rate
HV	Heritage Village	5	17–21	Sand and gravel (1)	3,544	1997–2001; well owner's records <sup>1</sup>
WF	Watertown Fire District	10	9–12	Sand and gravel (1)	2,450	1997–2001; well owner's records <sup>2</sup>
UW1	United Water Company	1	38 (screened 35–38)	Sand and gravel (1)	334	June–December 2001; well owner's records <sup>3</sup>
UW2	United Water Company	1	19 (screened 12–16)	Sand and gravel (1)	392	June–December 2001; well owner's records <sup>3</sup>
WT	Woodlake Tax District	3	9–12	Sand and gravel (1)	264	October 2001–September 2002; well owner's records <sup>4</sup>
WP	Woodbury Place Condominiums	1	12	Sand and gravel (1)	27	Population served: 72
WK	Woodbury Knolls Condominiums	1	38 (screened 9–38)	Crystalline bedrock (1)	98	Population served: 258
TC	Town in Country Condominiums	2	43 (screened 9–33) and 85	Crystalline bedrock (1 and 2)	91	Population served: 240
HH	Heritage Hill Condominiums	1	84	Crystalline bedrock (2)	45	Population served: 120
QH	Quassuk Heights Condominiums	3	61–107	Crystalline bedrock (2)	41	Population served: 108
RM	Romatic Manufacturing Co.	1	Unknown	Crystalline bedrock (2)	45	Population served: 120
NHS	Nonnewaug High School	1	Unknown	Crystalline bedrock (2)	322	Population served: 850

<sup>1</sup> Roy Adamitis, Heritage Village, written commun., 2003

<sup>2</sup> Ernie Coppock, Watertown Fire District, written commun., 2003

<sup>3</sup> Kevin Moran, United Water, written commun., 2003

<sup>4</sup> Woodlake Tax District, written commun., 2003

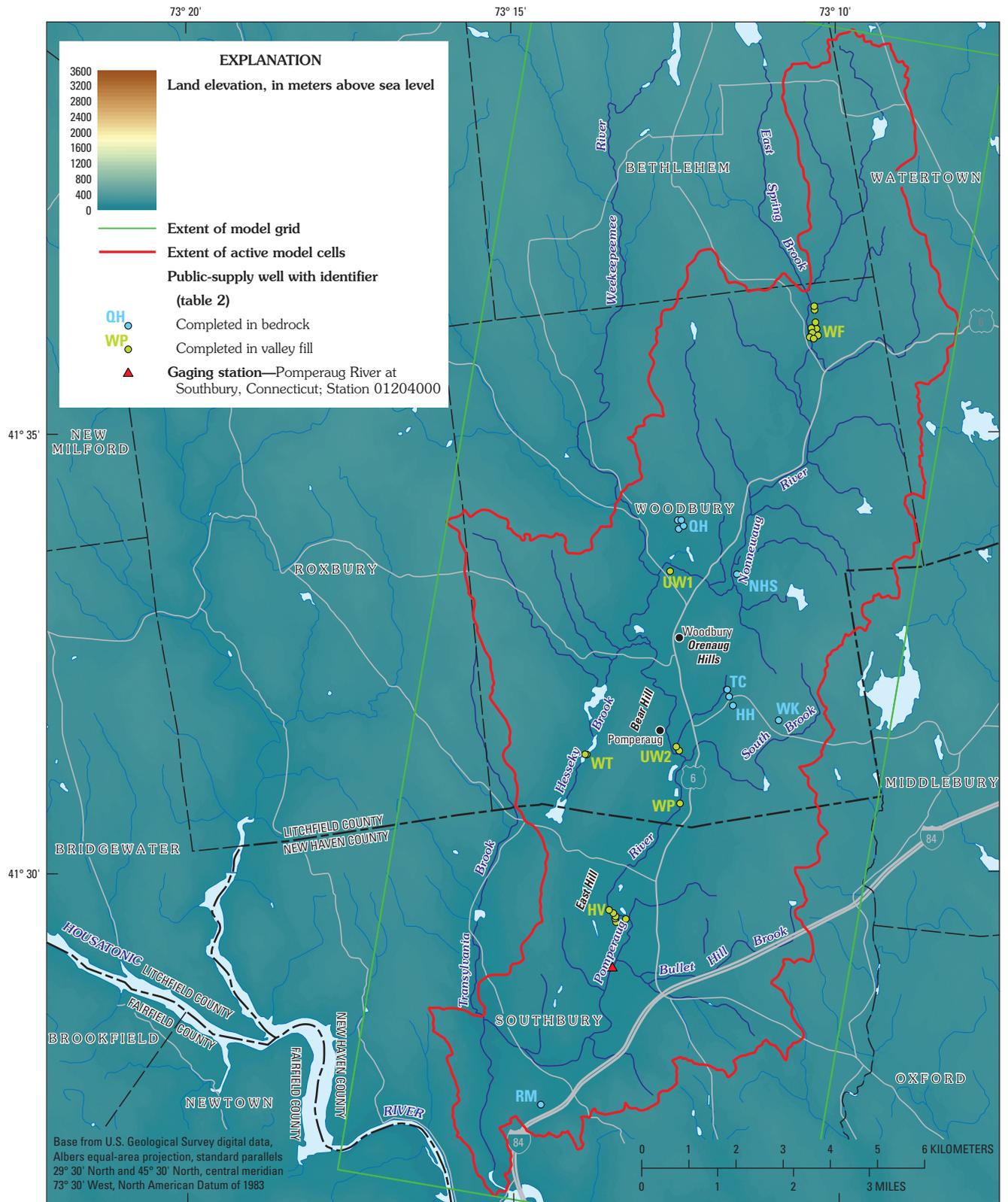


Figure 6.2. Topography, hydrologic features, and locations of public-supply wells, Pomperaug River Basin regional study area, Connecticut.

## Conceptual Understanding of the Ground-Water System

Ground water beneath the Pomperaug River Basin regional study area occurs in the glacial valley-fill deposits of the Pomperaug River valley and the underlying Mesozoic and Paleozoic bedrock (fig. 6.3). Recharge to the valley-fill aquifer is from infiltration of precipitation, surface-water flow from upland areas, and ground-water inflow from underlying bedrock. Ground water discharges to wells and surface-water features.

### Geologic Units and Hydraulic Properties

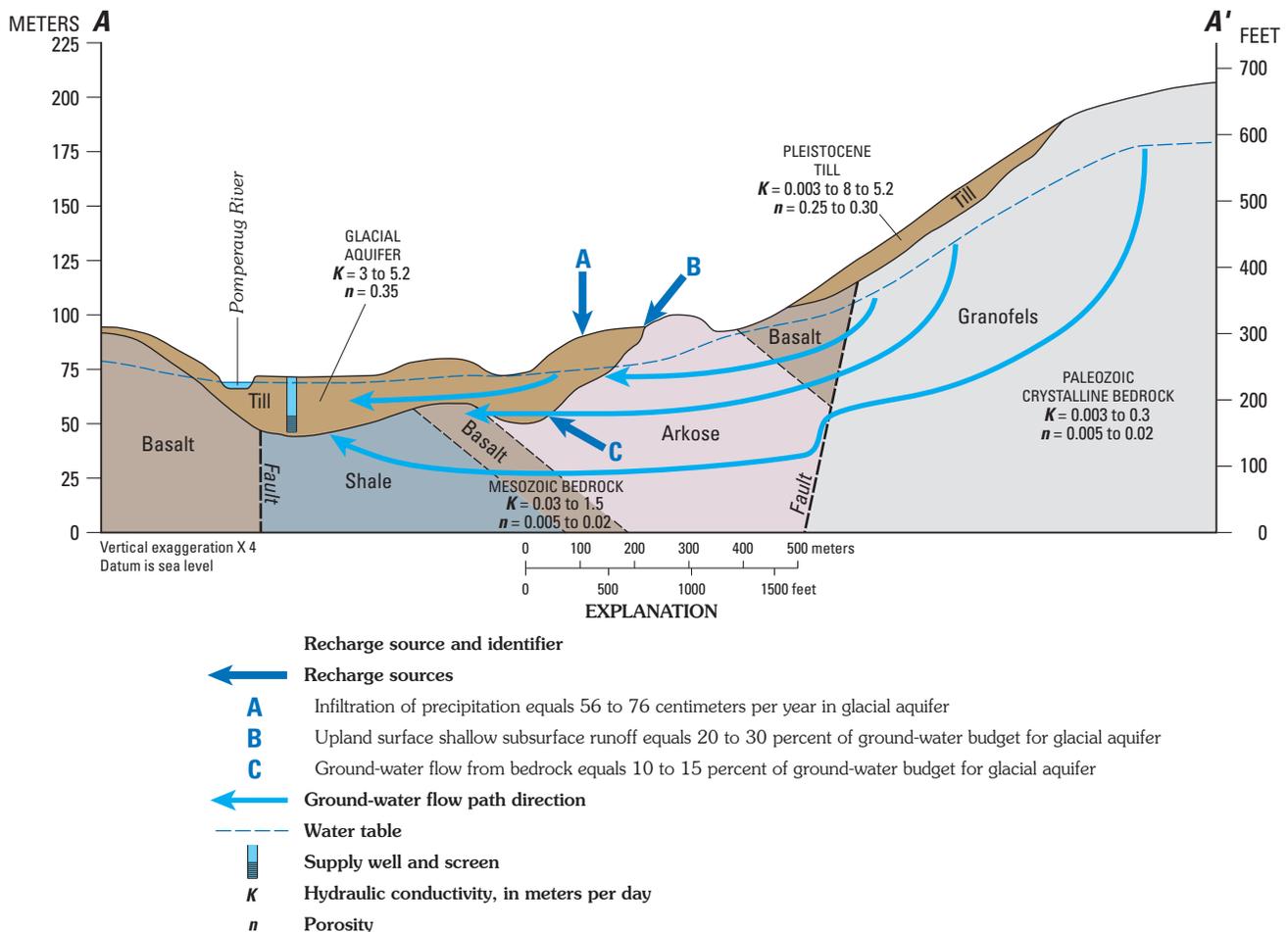
Geologic units in the Pomperaug River valley consist of Mesozoic sedimentary and volcanic bedrock within a structural basin in the central and western parts of the study area, surrounded by Paleozoic crystalline bedrock in upland areas; these consolidated units are overlain by Pleistocene-age glacial

till and valley-fill surficial deposits. The geologic setting and hydraulic properties of the bedrock and surficial deposits are presented in the following sections.

### Bedrock

The Pomperaug River valley in Woodbury and Southbury lies partly within a partial graben (Gates, 1954, 1959; Scott, 1974; Stanley and Caldwell, 1976) composed of Mesozoic-age sedimentary and volcanic rocks. The Pomperaug fault extends north to south through the study area (fig. 6.4) and marks the eastern limit of Mesozoic-age rocks. East Hill, Bear Hill, and the Orenaug Hills (fig. 6.2) are topographically high areas in the Pomperaug River valley underlain by erosion-resistant basalts. Highlands east and west of the valley and structural basin are underlain by crystalline bedrock (Rodgers, 1985).

The Mesozoic-age sequence consists of three basalt layers interbedded with shale, arkosic sandstone, and conglomerate, which dip eastward at various angles but average about 40° (Scott, 1974). The Mesozoic bedrock in the structural



**Figure 6.3.** Conceptual ground-water flow patterns, representative hydraulic properties, and recharge rates, Pomperaug River Basin regional study area, Connecticut.

basin was fully penetrated at a depth of 376 m in an oil test well drilled in the late 1800s near Southbury (fig. 6.2) (Hovey, 1890). Thicknesses elsewhere are unknown. Faults, which are too numerous to show at the scale on figure 6.4, cause offsets of beds. Mapped faults are oriented approximately northeast to southwest in the southern part of the study area and north to south in the northern part of the study area (Scott, 1974; Rodgers, 1985).

Paleozoic-age crystalline rocks underlying the western part of the study area include granite, quartzite, schist, and gneiss (Scott, 1974; Gates, 1954). Numerous folds have been mapped in the crystalline rocks. Foliation planes typically dip steeply at angles exceeding 45°. Foliation strike varies widely, but a north-northwest to south-southeast trend appears to dominate in much of the study area (Scott, 1974; Gates, 1954).

Wells completed in bedrock obtain most of their water from fractures. Aquifer-test data are not available for bedrock wells in the study area, but driller-reported yields and water levels during pumping are indicators of transmissive properties. Average yields from numerous wells completed in Paleozoic-age crystalline rocks and Mesozoic-age rocks are similar, but wells completed in Paleozoic crystalline rocks are typically deeper than those completed in Mesozoic rocks. A sample of driller's reports for 60 domestic wells was summarized for this study. Yields reported for 14 wells completed in Mesozoic rocks average about 37 m<sup>3</sup>/d and depths average 83 m. Yields for 46 wells completed in Paleozoic crystalline rocks average about 49 m<sup>3</sup>/d and depths average 99 m. Starn and others (2000) report an average hydraulic conductivity of 0.18 m/d for Paleozoic rocks and 1.43 m/d for Mesozoic rocks in the Transylvania Brook Basin, a tributary to the Pomperaug River west of the study area (fig. 6.2). Lower values of 0.006 to 0.03 m/d for crystalline rocks in northern New Hampshire were determined by model calibration (Tiedeman and others, 1997). Lyford and others (2003) report hydraulic conductivity values that range from 0.006 to 4.3 m/d near public-supply wells completed in metamorphic rocks in eastern Massachusetts.

Bedrock transmissivities estimated by applying the Cooper-Jacob formula (Cooper and Jacob, 1946; Fetter, 1994) for driller-reported yields, drawdowns, and pumping times average about 1.9 m<sup>2</sup>/d for Mesozoic rocks and about 1.0 m<sup>2</sup>/d for Paleozoic rocks. For the average thicknesses of rocks penetrated by wells, hydraulic conductivity values average about 0.03 m/d for Mesozoic rocks and 0.01 m/d for Paleozoic rocks. Because of uncertainties associated with the data, method of analysis, and small data set, these estimates are presented as "order-of-magnitude" values and support the concept that Mesozoic rocks are more transmissive than Paleozoic rocks.

Water-bearing fractures commonly are found along foliation planes in metamorphic rocks and bedding planes in Mesozoic rocks (Janet Stone, U.S. Geological Survey, oral commun., 2002; Walsh, 2001a, 2001b, 2002). A dominant high-angle foliation in metamorphic rocks and numerous high-angle fractures in Mesozoic rocks (Gates, 1954; Scott, 1974) indicate the rocks are well connected vertically, but values of

vertical hydraulic conductivity are not available. Lyford and others (2003) report vertical conductance (vertical hydraulic conductivity divided by thickness) values of 0.0015 to 0.04 1/d for two areas where high-angle fractures are present and metamorphic rocks are well connected vertically to surficial materials. Porosity values reported for crystalline bedrock range from 0.005 to 0.02 (Ellis, 1909; Heath, 1989; Barton and others, 1999).

## Surficial Materials

Surficial materials are largely glacially derived and include till deposited on bedrock and glacial sand and gravel outwash deposited in valleys (fig. 6.4). Also present but not shown separately on figure 6.4 are Holocene alluvial materials, typically less than 3 m thick, which were deposited by streams after glaciers receded. The alluvial materials commonly include organic matter (Pessl, 1970).

Till includes a surface till unit (also called thin till) deposited by the last glacial ice sheet and a thick till unit (also called drumlin till) deposited during an earlier glacial epoch and compacted by the last ice sheet (Melvin and others, 1992). The surface till unit is fairly continuous and typically less than 5 m thick. The thick till unit typically is found in stream-lined hills, exceeds a thickness of 15 m in places, and is covered by surface till. The depth to bedrock reported by drillers for 60 wells completed in bedrock, mostly in upland areas, ranges from 0.9 to 46 m and averages 12 m. The surface till averages 75 percent sand or coarser and 25 percent silt and clay and typically is not oxidized except in places along sand and gravel lenses. The thick till typically is finer grained, averaging 60 percent sand or coarser and 40 percent silt and clay and is oxidized throughout (Pessl, 1970).

The hydraulic properties of till described by Melvin and others (1992) for Connecticut are reasonable for the study area. They report an average hydraulic conductivity of 0.8 m/d for loose surface till and 0.02 m/d for compact drumlin till derived from crystalline rocks. Horizontal hydraulic-conductivity values for surface and drumlin tills range from 0.0009 to 20 m/d, and vertical hydraulic-conductivity values range from 0.004 to 29 m/d. Porosity ranges from 0.2 for compact drumlin till to 0.35 for surface till (Melvin and others, 1992).

Stratified, glacially derived sediments underlie about 33 km<sup>2</sup> of the valley, or about 26 percent of the study area. The valley-fill deposits include sand and gravel deposited by glacial streams, usually in contact with stagnant ice masses, and silt, sand, and gravel deposited in glacial Lake Pomperaug. The distribution of valley-fill sediments is consistent with the morphosequence depositional model for glacial sediments (Stone and others, 1998; Randall, 2001). A morphosequence is defined as "a body of stratified drift that was laid down by meltwater when deposition was controlled by a specific base level such as a proglacial lake or spillway; the deposits become generally finer distally and their upper surface (where not collapsed) slopes smoothly in the same distal direction" (Randall, 2001, p. 178). Several glacial-lake stages are appar-

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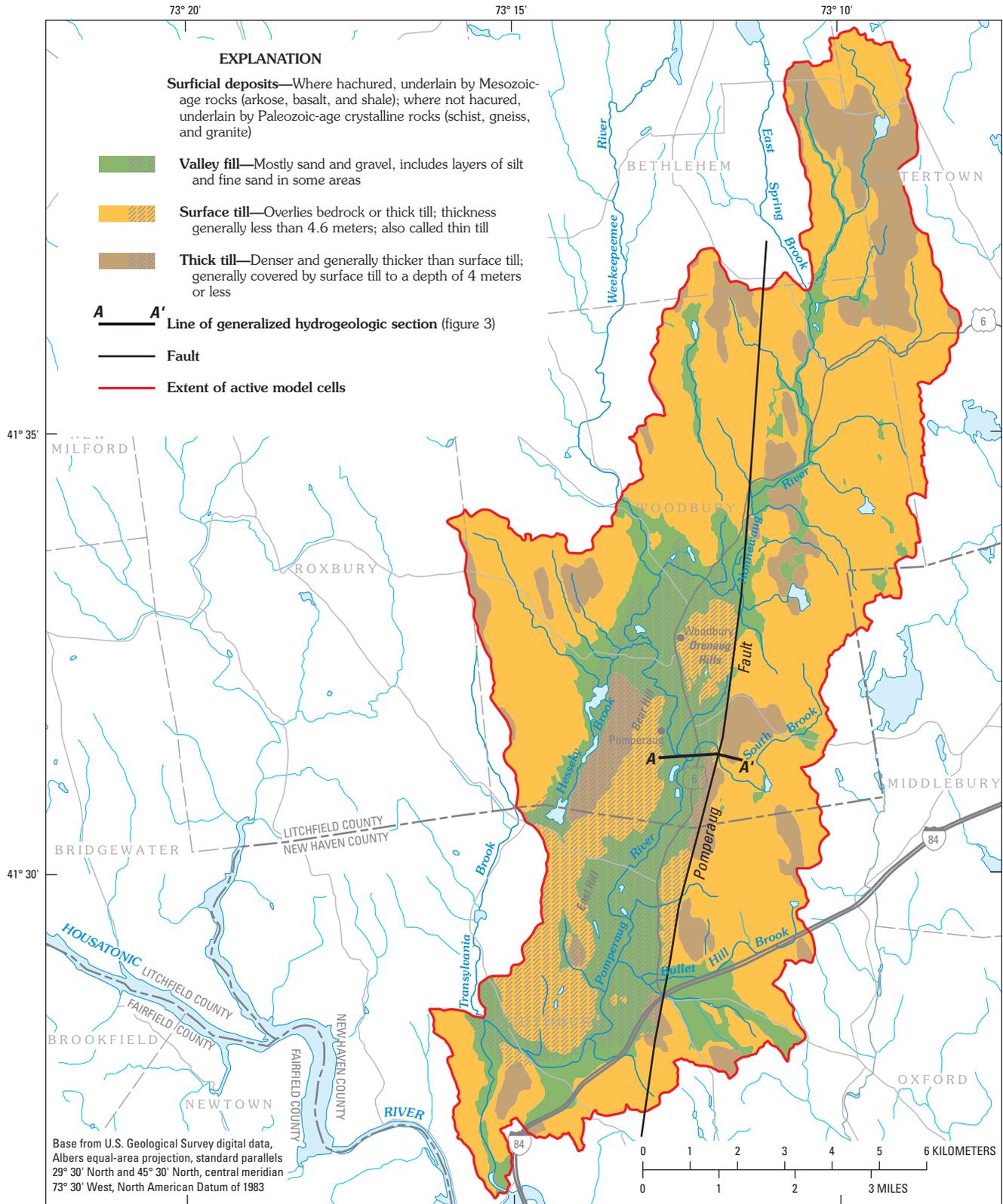


Figure 6.4. Bedrock and surficial geologic units, Pomperaug River Basin regional study area, Connecticut.

ent in relative altitudes of deposits. The last stage of the lake drained when a dam consisting of sand and gravel at Pomperaug (fig. 6.2) was breached (Pessl, 1970). Coarse-grained materials predominate at the land surface, but as much as 47 m of fine-grained sand, silt, and clay has been identified in the subsurface in some parts of the Pomperaug Valley (Mazzaferro, 1986a).

The hydraulic conductivity of outwash deposits, which was determined on the basis of aquifer tests and specific-capacity tests, ranges from 1.5 m/d for fine materials to 76 m/d or more for gravel (Mazzaferro, 1986a; Starn and others, 2000). The greatest hydraulic conductivity areas are mapped near the towns of Woodbury, Pomperaug, and Southbury (Grady and Weaver, 1988). The vertical hydraulic conductivity for sand and gravel has not been determined, but a ratio of 10 for horizontal to vertical commonly is assumed (Kontis and others, 2004). The porosity of sand and gravel typically ranges from 0.3 to 0.45 (Morris and Johnson, 1967; Masterson and others, 1997; Mullaney and Grady, 1997).

## Ground-Water Occurrence and Flow

Ground water generally is unconfined and within 15 m of the land surface throughout much of the Pomperaug River Basin regional study area. Depths to water exceed 15 m for some areas of sand and gravel near valley walls and in an area of deltaic sediments near Woodbury (Mazzaferro, 1986b). The valley-fill saturated thickness ranges from zero near the contact with upland till to 37 m near Woodbury (Grady and Weaver, 1988).

Ground-water flow in upland areas includes shallow subsurface flow through surface till and soil to nearby wetlands and stream channels and deep flow through thick till and fractured bedrock to more distant discharge points, including tributaries to the Pomperaug River and valley fill. During periods of high recharge, when the water table is near the land surface, the shallow flow and short flow paths predominate. However, water levels are lower during extended dry periods, and deep flow along longer flow paths predominates. Meinzer and Stearns (1929) report numerous dug wells and ground-water depths generally less than 9 m in upland areas of the Pomperaug River Basin. Driller-reported water levels that average 7.3 m in depth for wells completed in Paleozoic rocks also support the concept of a water table generally less than 9 m deep.

Ground-water flow directions shown in figure 6.5 are based on a water-table map for the valley fill presented by Mazzaferro (1986a) and basin-wide flow paths simulated as part of this study. In general, ground-water flow is from upland recharge areas toward discharge areas along the Pomperaug River and its tributaries. Pumping from public-supply wells may affect ground-water flow locally, but depressions in the water table caused by pumping are not apparent at the 3-m contour interval used to map the water table in valley fill

(Mazzaferro, 1986a). Conceptually, pumping has a minimal effect on area-wide flow patterns.

## Water Budget

Recharge in upland areas is largely by infiltration of precipitation. Other minor sources include wastewater return from septic systems and leakage from ponds and streams. Recharge rates in upland areas are not well understood in New England, but controlling factors appear to include the distribution of surface till and topography. Areas of shallow ground water can be extensive during wet periods, particularly during the spring. In these areas, a major control on recharge rates is the depth to the water table and the rate at which ground water at the water table drains vertically or laterally. The vertical and lateral flow of ground water varies widely in upland areas and relates to the transmissivity of till and bedrock, topographic relief, and hydraulic gradient at the water table. Annual recharge rates, therefore, can vary widely from near zero in wetland discharge areas where the water table is perennially at or near the land surface to rates that approach annual runoff rates.

Numerous streamflow records in Connecticut have been analyzed for the ground-water runoff component, which is an approximation of ground-water recharge. For basins underlain principally by till, data presented by Mazzaferro and others (1979) indicate ground-water runoff is approximately 33 percent of total runoff. Ground-water runoff from uplands in the Pomperaug River Basin would average about 20 cm/yr on the basis of the statewide analysis. Mazzaferro (1986a) estimated long-term effective recharge rates (ground-water recharge minus ground-water evapotranspiration) of about 18 cm/yr. Analysis of streamflow data in similar upland settings using the programs of Rutledge (1993, 1997, 1998) typically yield higher recharge rates of 38 cm/yr or more (Bent, 1995, 1999; Robert Flynn and Gary Tasker, U.S. Geological Survey, written commun., 2003). Starn and others (2000) determined area-averaged recharge rates of 56 cm/yr for areas underlain by Mesozoic rocks and 20 cm/yr for areas underlain by crystalline rocks on the basis of the statewide analysis of ground-water runoff and numerical modeling of ground-water flow near Transylvania Brook. A water-budget study of the Pomperaug River Basin by Meinzer and Stearns (1929) for 1913–1916 indicated basin-wide ground-water recharge averaged 39.5 cm/yr and precipitation averaged 113 cm/yr. They stated that nearly one-half of the ground-water recharge was lost to evapotranspiration.

Major recharge sources in areas underlain by valley fill include direct infiltration of precipitation, ground-water inflow from bedrock, runoff from bordering hillslopes, and infiltration from tributary streams (Lyford and Cohen, 1988; Randall and others, 1988). Other sources include induced infiltration from streams near wells and disposal of wastewater from septic systems. Direct infiltration of precipitation to valley fill probably approaches annual runoff rates (precipitation

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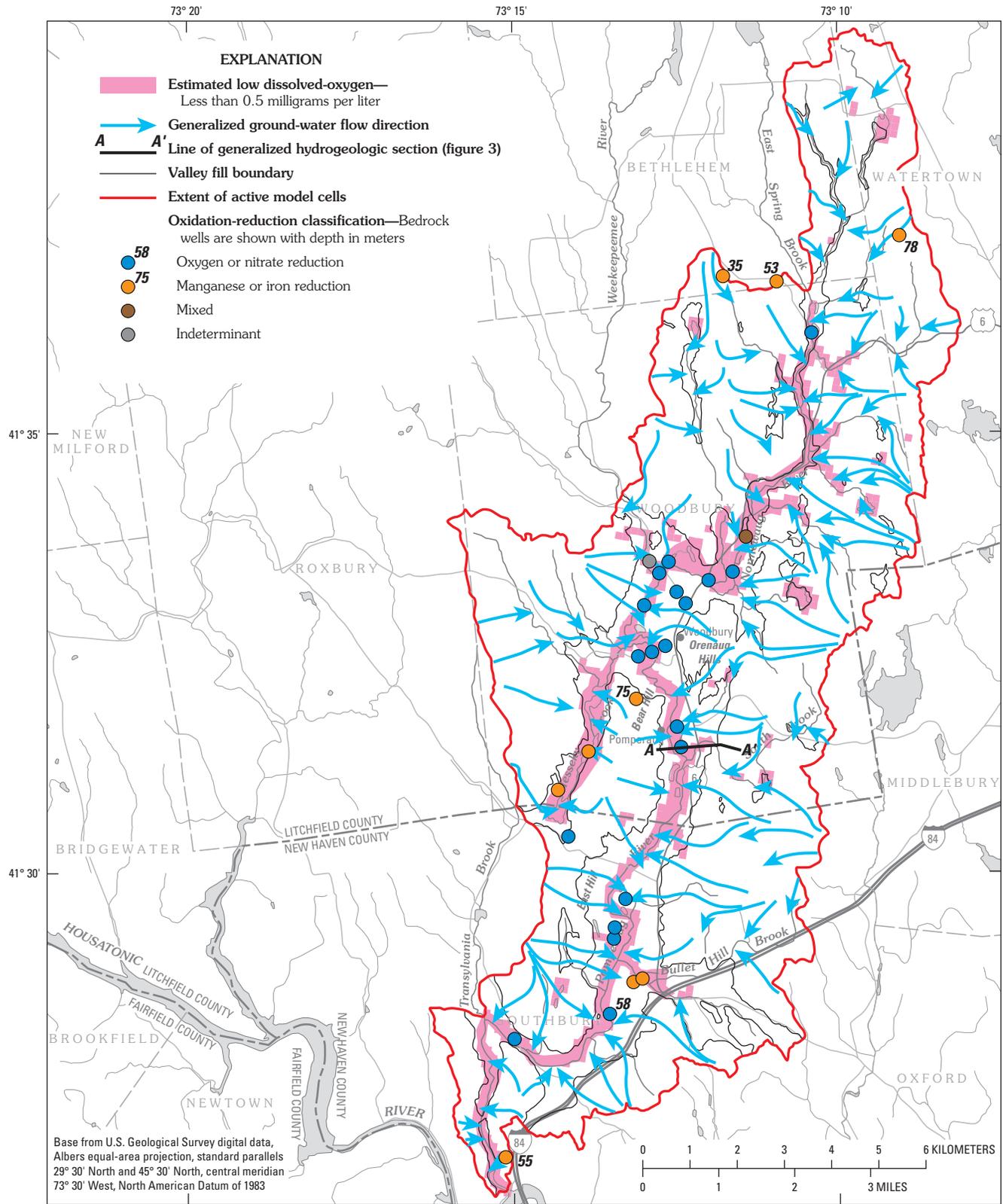


Figure 6.5. Wells sampled, oxidation-reduction classification zones, and directions of ground-water flow, Pomperaug River Basin regional study area, Connecticut.

minus evapotranspiration) or about 61 cm/yr (Randall, 1996; Morrison and others, 2002). Mazzaferro (1986a) estimated long-term effective recharge rates of 48 to 51 cm/yr for areas underlain by sand and gravel. Starn and others (2000) simulated rates of 56 cm/yr for sand and gravel in the Transylvania Brook area. Inflow rates from crystalline rocks typically are small relative to other sources, but inflow rates from Mesozoic rocks, which potentially receive more recharge from precipitation and are more transmissive than crystalline rocks, may be a major source of recharge to valley fill in some areas. Recharge rates from upland hillslopes that border valley-fill materials vary with the size of the hillslope contributing area and can account for 50 percent or more of the total recharge to valley-fill materials (Williams and Morrissey, 1996; Morrissey and others, 1988). Water-budget summaries, which were compiled from ground-water flow models in New England, indicated that from 30 to 60 percent of the inflow to valley fill is from upland sources. Natural infiltration from streams that cross valley fill from upland areas also can be a major component of recharge to valley-fill aquifers in some settings (Williams and Morrissey, 1996). An analysis of streamflow data for the Pomperaug River at Southbury, using the programs of Rutledge (1993, 1997, 1998), indicated that for 1995–96, a period when total runoff was about 5 cm above long-term average runoff, basin-wide recharge was 70 to 80 percent of total runoff, or 46 to 53 cm/yr (J.J. Starn, U.S. Geological Survey, written commun., 2002).

## Ground-Water Quality

Ground-water quality data for wells completed in the valley-fill aquifer of the study area indicate dissolved-solids concentrations are generally less than 200 mg/L (Mazzaferro and others, 1979; Mazzaferro, 1986a; Grady and Weaver, 1988). Ground water generally is of the calcium-sodium-magnesium-bicarbonate-chloride type, and the pH typically

ranges from 6.0 to 7.5 (Mazzaferro and others, 1979; Mazzaferro, 1986a; Grady and Weaver, 1988). Some water samples in the study area indicate contamination from anthropogenic sources, including road salt, agricultural chemicals, petroleum hydrocarbons, chlorinated compounds, and septic systems. A study by Grady and Weaver (1988) of the effects of land use on ground-water quality in shallow monitoring wells found several contaminants associated with human activities in residential, commercial, light industrial, and agricultural land-use settings. Concentrations of natural contaminants, including radionuclides (Thomas and McHone, 1997) and arsenic (Brown and Chute, 2002), can be high in fractured bedrock aquifers in parts of Connecticut and potentially migrate to community water supplies in adjacent stratified-drift aquifers. High concentrations of radon have been associated with crystalline rocks (the Nonnewaug Granite and the Collinsville and Taine Mountain Formations) (Thomas and others, 1988; Thomas and McHone, 1997).

Ground water in most of the stratified glacial aquifer is oxygen and nitrate reducing, but in some areas near the central part of the valley, manganese- and iron-reducing conditions are present where water along longer flow paths discharge to surface-water bodies (fig. 6.5). In these waters, concentrations of dissolved oxygen typically are low, dissolved iron and manganese concentrations are high, and nitrate concentrations generally are low or below detection. Organic-rich sediments beneath surface-water bodies and in wetlands also can consume dissolved oxygen and create manganese- and iron-reducing shallow ground water, as observed in a flow-path study by Mullaney and Grady (1997) in a glacial aquifer in north-central Connecticut. Ground water in the fractured bedrock generally is older than water from the glacial aquifer, and tends to be manganese and iron reducing. Ground water that has flowed through rocks of Mesozoic or Paleozoic age before passing into the glacial aquifer could reflect chemical characteristics of the bedrock.

## Ground-Water Flow Simulations

A steady-state model of ground-water flow in the study area was developed using MODFLOW-2000 (Harbaugh and others, 2000) to estimate aquifer-system properties, delineate areas contributing recharge to public-supply wells, and support future local modeling efforts. The model represents average ground-water flow conditions from 1997 to 2001. Model input includes boundary conditions, model stresses, and hydraulic properties. The preprocessor Argus ONE (Argus Interware, 1997) with the graphical interface for MODFLOW (Winston, 2000), using MODFLOW-2000 (Harbaugh and others, 2000), provided flexibility for setting up model grids, layer thicknesses, and stream characteristics. Aquifer-system and model characteristics are summarized in table 6.3.

### Modeled Area and Spatial Discretization

The Pomperaug River Basin regional ground-water flow model encompasses an area of 128 km<sup>2</sup> (fig. 6.6). A no-flow (zero-flux) boundary surrounds the modeled area, which assumes that ground-water divides are coincident with topographic divides, that inflow to the modeled area as underflow from three tributary basins is negligible, and that underflow at the mouth of the Pomperaug River is negligible.

Experiments with uniform model grid sizes consisting of 30.5-m- and 152.4-m-square cells indicated simulated water budgets, flow paths, and contributing recharge areas were nearly identical for the two cell sizes. The calibrated model discussed here is for the 152.4-m cell size because the larger spacing was more numerically stable, computer simulation times were shorter, and output data were easier to manage than those for the 30.5-m cell size. The 30.5-m cell size was later used for particle-tracking simulations to delineate areas contributing recharge to public-supply wells. Two layers that parallel the land surface were selected to represent the vertical dimension. Layer 1 is 46 m thick and represents till and shallow bedrock in upland areas and stratified, glacially derived sediments and shallow bedrock in the valleys. Layer 2 represents a 107-m- thick section of bedrock. It is assumed that most ground water flows through a total thickness of about 152 m. Early attempts to use a uniform 15-m thickness for layer 1 and four layers resulted in numerical instabilities that could not be resolved. The two-layer model was generally stable for a layer 1 thickness of 46 m. Layer 1 was specified as convertible to unconfined where heads were below the top of the layer, and layer 2 was specified as confined.

### Boundary Conditions and Model Stresses

Model stresses include streams, recharge, and extraction wells. Perennial streams were simulated using the MODFLOW stream package (Prudic, 1989). The stream package accounts for gains and losses in the simulated streams and

routes flow from upstream reaches to downstream reaches. The ends of stream segments were placed at mapped stream origins in headwater areas, at stream intersections, and at major changes in stream-channel slope. The stream altitudes were interpolated linearly within a segment. This approach closely matched actual stream altitudes at stream reaches for low-gradient, uniformly sloped main stems but was less accurate for tributary streams with high-gradient, nonuniform slopes. The top of the streambed was placed 0.9 m below the stream stage, and the bottom of the streambed was placed 1.2 m below the stream stage. The Nonnewaug, Weekeepeme, and Pomperaug Rivers were assumed 15 m wide except near the Watertown Fire District Wells (WF) where a 30-m width was assigned to account for diversions from the Nonnewaug River through recharge ponds. All other streams were assumed to be 3 m wide. A streambed hydraulic conductivity of 0.3 m/d was assumed for all streams on the basis of literature-reported values (Kontis and others, 2004).

Recharge was applied in five zones defined by geology (fig. 6.7), and recharge rates were assigned so basin runoff approximated 70 to 80 percent of long-term average runoff measured for the Pomperaug River at Southbury. Evapotranspiration of ground water was accounted for in the recharge estimates but was not modeled explicitly. A recharge rate of 56 cm/yr was used for the valley fill by Starn and others (2000) for the Transylvania Brook area and was also applied to areas underlain by valley fill in this study. Surface runoff is limited in areas underlain by valley-fill materials, thus the recharge rate should approximate runoff rates (Lyford and Cohen, 1988). A rate less than the basin runoff rate of about 61 cm/yr accounts for some storm runoff from impermeable surfaces. A recharge rate of 61 cm/yr was applied on hillslopes that adjoin the valley fill to account for water that runs off of these areas and recharges the valley fill near the valley edges. Most areas underlain by Mesozoic rocks form hillslopes adjacent to valley fill, so a recharge rate of 61 cm/yr also was applied in this zone. This rate is similar to a rate of 56 cm/yr used by Starn and others (2000) in the Transylvania Brook area. A rate of 38.1 cm/yr was applied in thick till and thin till areas underlain by crystalline rocks.

Discharge wells were placed at locations of public-supply wells completed in sand and gravel and bedrock. Wells completed in valley fill were placed in layer 1. Wells in upland areas that service condominium units and the Romatic Manufacturing Company (RM) are completed in bedrock. All but two of the bedrock wells were placed in layer 2. A well 43 m deep at the Town in Country Condominiums (TC) and a well 38 m deep at the Woodbury Knolls Condominiums (WK) were placed in layer 1 because of depths less than the thickness of layer 1. A well completed to an unknown depth in bedrock at Nonnewaug High School (NHS) is in a valley setting but also was placed in layer 2. Extraction rates were set to measured or estimated average rates (combined pumping rate; table 6.2).

Screened intervals for wells in sand and gravel and producing intervals for wells in bedrock were available for only United Water Company Wells #1 and #2 (UW1 and UW2),

**Table 6.3.** Summary of aquifer-system and model characteristics, Pomperaug River Basin regional study area, Connecticut

[m, meters; m/d, meters per day; cm/yr, centimeters per year]

Characteristic	Measured or estimated range	Simulated value
<b>Thickness</b>		
Valley fill	0 to 61 m	Total thickness of layer 1 is 46 m, which may include any of the following: valley fill, till, and bedrock
Thick till	5 to 46 m	
Surface till	0 to 5 m	
Bedrock	Less than 152 m	107 m
<b>Hydraulic conductivity</b>		
Valley fill	1.5 to 76 m/d	Less than 3 m thick: 0.12 m/d 3 to 15 m: 6.28 m/d Greater than 15 m thick: 5.7 m/d Gravel over fines: 2.8 m/d
Thick till	0.003 to 0.3 m/d	0.12 m/d
Surface till	0.003 to 3 m/d	0.09 m/d
Crystalline bedrock	0.003 to 0.3 m/d	0.03 m/d
Mesozoic bedrock	0.03 to 1.5 m/d	0.09 m/d
<b>Ratio of horizontal to vertical hydraulic conductivity</b>	1.0 to 10	1
<b>Porosity</b>		
Valley fill	0.3 to 0.45	Less than 3 m thick: 0.01 3 to 15 m: 0.07 Greater than 15 m thick: 0.23 Gravel over fines: 0.23
Thick till	0.25	0.08
Surface till	0.2 to 0.35	0.035
Crystalline bedrock	0.005 to 0.02	0.02
Mesozoic bedrock	0.005 to 0.02	0.02
<b>Stream characteristics</b>		
Width	3 to 30 m	Near Watertown Fire District wells: 30 m; Main stems: 15 m; tributaries: 3 m
Hydraulic conductivity of streambed	0.1 to 3 m/d	0.3 m/d
Thickness of streambed	0.3 to 1.5 m	0.3 m
<b>Recharge rates</b>		
Hillslope	38 to 66 cm/yr	61 cm/yr
Valley fill	48 to 61 cm/yr	56 cm/yr
Mesozoic rocks	38 to 66 cm/yr	61 cm/yr
Surface till	20 to 6 cm/yr	38 cm/yr
Thick till	20 to 56 cm/yr	38 cm/yr

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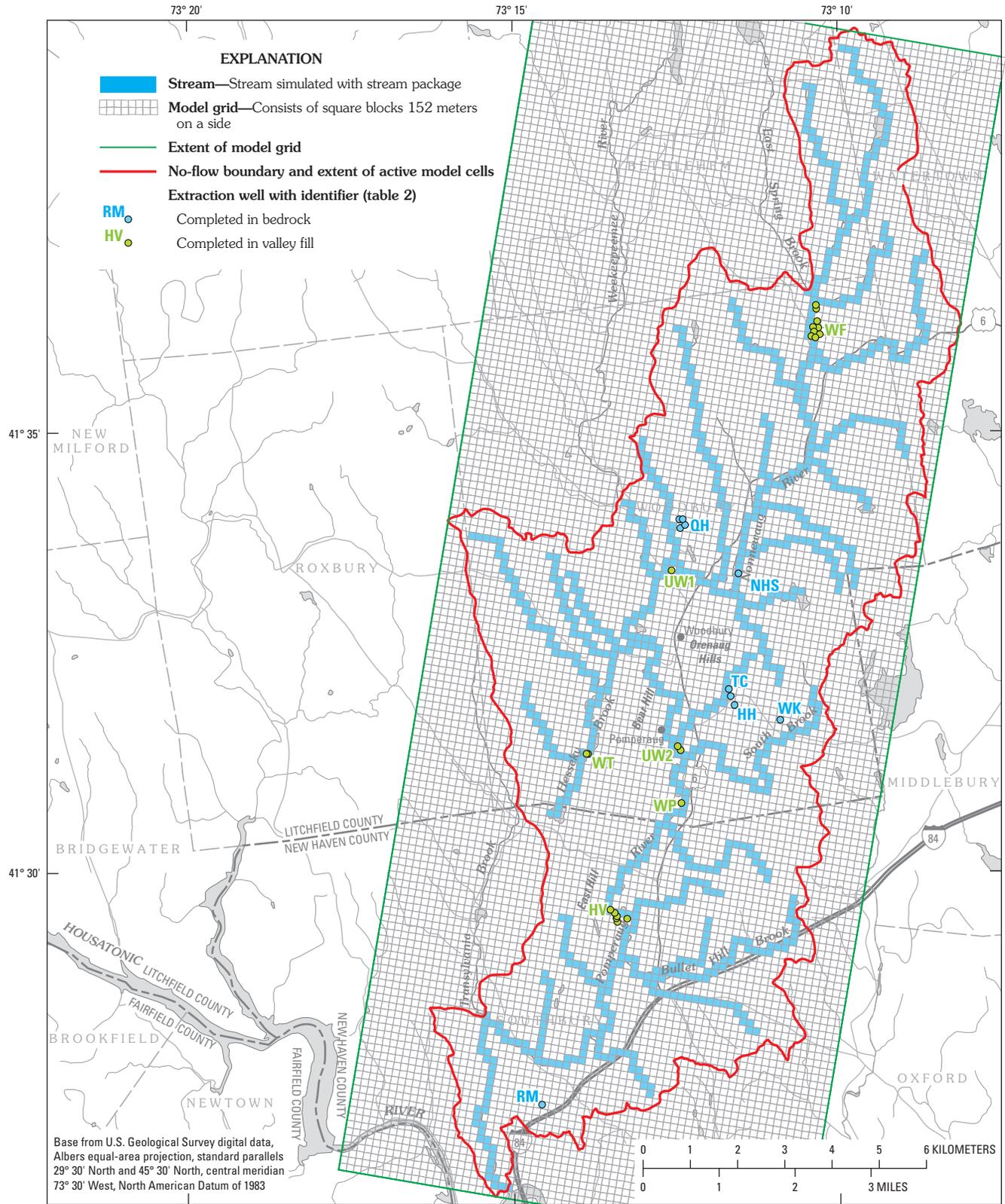


Figure 6.6. Ground-water flow model grid and simulated streams and wells, Pomperaug River Basin regional study area, Connecticut.

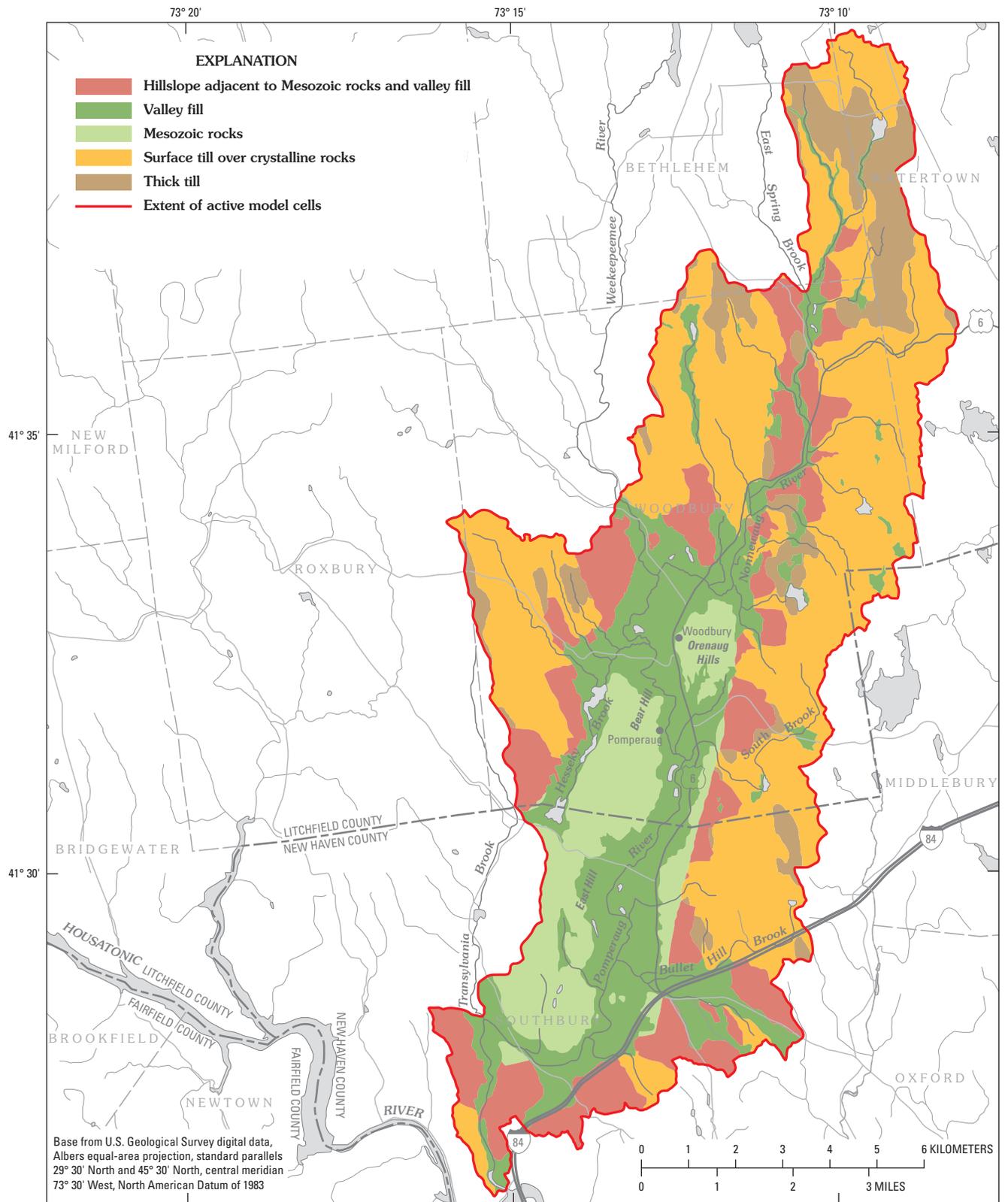


Figure 6.7. Ground-water recharge zones, Pomperaug River Basin regional study area, Connecticut.

Woodbury Knoll Condominium (WK), and Town in Country Condominium (TC) (table 6.2). For purposes of tracking particles, a screen length of 6.1 m at the bottom of the well was assumed for wells completed in valley fill, and a producing interval from the top of layer 2 to the bottom of the well was assumed for bedrock wells. For Romatic Manufacturing Company (RM) and Nonnewaug High School (NHS), where well depths are unknown, the producing interval was assumed to be the thickness of layer 2.

## Aquifer Hydraulic Properties

Hydraulic-conductivity zones for each layer were defined on the basis of the mapped distribution of geologic units and saturated thicknesses presented by Grady and Weaver (1988). Layer-1 zones included surface till and thick till zones in uplands and four zones in valley fill (fig. 6.8). The zones for valley-fill materials are defined largely on the basis of saturated thickness of sand and gravel and are best visualized as transmissivity zones rather than hydraulic-conductivity zones because layer-1 thickness generally is greater than actual geologic-unit thickness. These zones include (1) areas along the valley wall where the saturated thickness is less than 3 m, (2) areas where the saturated thickness is 3 to 15 m, (3) areas where the saturated thickness is greater than 15 m, and (4) a fairly extensive area near North Woodbury where coarse materials overlie fine materials. The hydraulic-conductivity values summarized in table 6.3 for valley-fill zones were refined somewhat from initial estimates by the parameter-estimation option in MODFLOW-2000. The hydraulic-conductivity zones for layer 2 include one for Paleozoic crystalline rocks and a second for the more transmissive Mesozoic rocks (fig. 6.4).

Porosity values for layer 1 were adjusted for thickness to simulate approximate cross-sectional pore areas in surficial materials and, thereby, more accurately simulate lateral traveltimes through surficial materials. Model porosities were calculated by multiplying estimated actual porosities by the ratio of saturated thickness to the thickness of layer 1 (46 m). For example, a saturated thickness of 4.6 m for thin till divided by a layer 1 thickness of 46 m and multiplied by an estimated porosity of 0.35 yields a model porosity of 0.035. Estimated and simulated porosity values for layer 1 zones are summarized in table 6.3. A uniform porosity of 0.02 was used for layer 2 to represent fracture porosity in bedrock.

## Model Calibration

The Pomperaug River Basin regional ground-water flow model was calibrated by manually adjusting model-input parameters for hydraulic conductivity and comparing model-computed to measured hydraulic heads. Data used for model calibration include average water levels reported by Mazzaf-erro (1986a) for January 1979 to February 1980 and for one USGS observation well (SB-39) for 1991 to 2002. Water-level data from driller's logs for upland areas indicated a shallow water table but were not used explicitly for model calibration. The calibration goal was to approximately simulate observed heads in valley fill with a uniform distribution of residuals (measured minus model-computed heads) and a shallow water table that approximated the land-surface configuration in upland areas. Streamflow data were not available for model calibration.

The overall goodness of fit of the model to the observation data was evaluated using summary measures and graphical analyses. The root-mean-squared error (RMSE), the range, the standard deviation, and the standard-mean error of the residuals (SME), were used to evaluate the model calibration. The RMSE is a measure of the variance of the residuals and was calculated as:

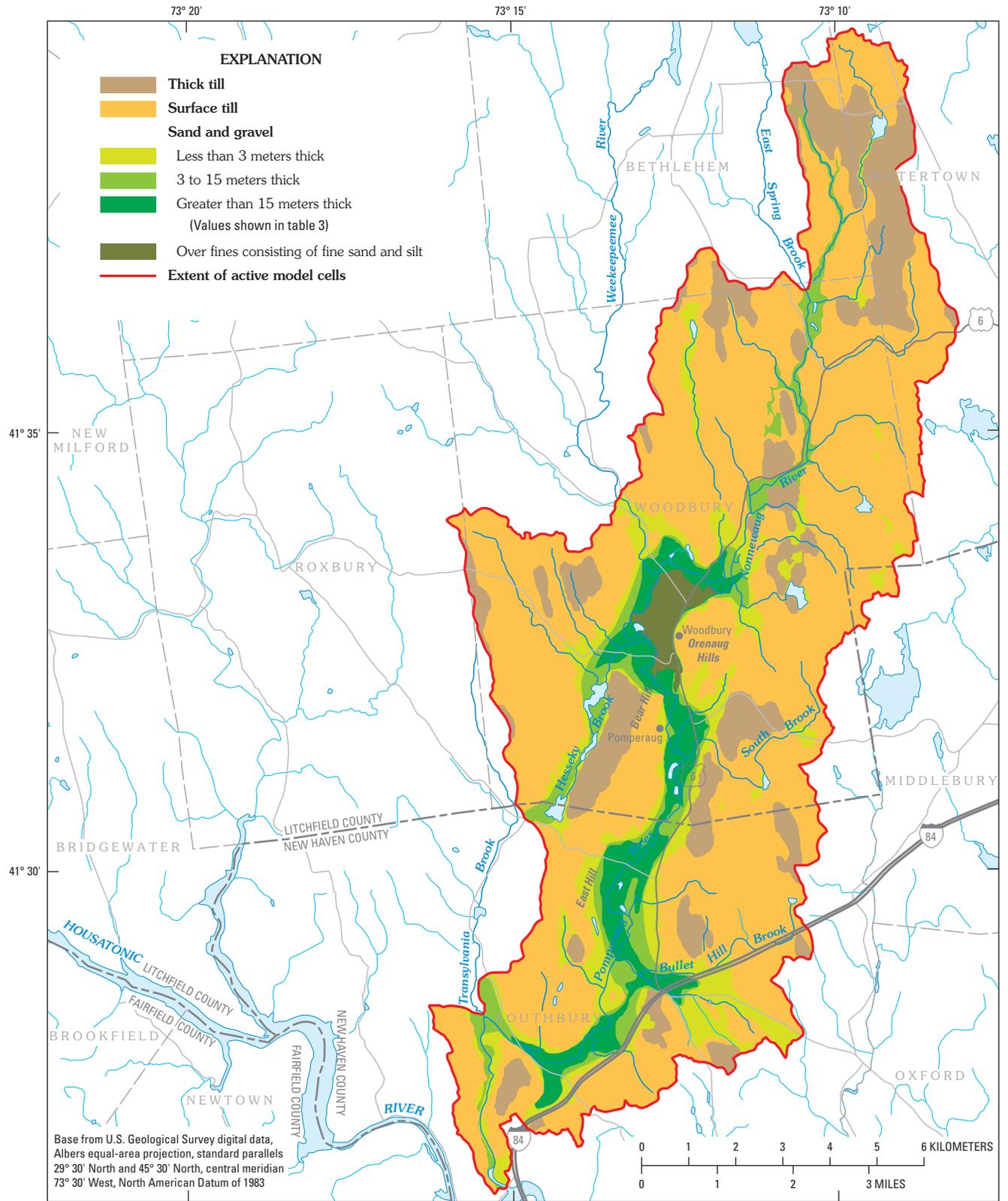
$$RMSE = \sqrt{\frac{\sum_{i=1}^N (h_{meas} - h_{sim})^2}{N}}$$

where  $h_{meas}$  is the measured hydraulic head,  $h_{sim}$  is the model-computed (simulated) hydraulic head,  $(h_{meas} - h_{sim})$  is the head residual, and  $N$  is the number of wells used in the computation. If the ratio of the RMSE to the total head change in the modeled area is small, then the error in the head calculations is a small part of the overall model response (Anderson and Woessner, 1992).

The SME was calculated as:

$$SME = \frac{\sigma(h_{meas} - h_{sim})}{\sqrt{N}}$$

where  $\sigma(h_{meas} - h_{sim})$  is the standard deviation of the residuals.

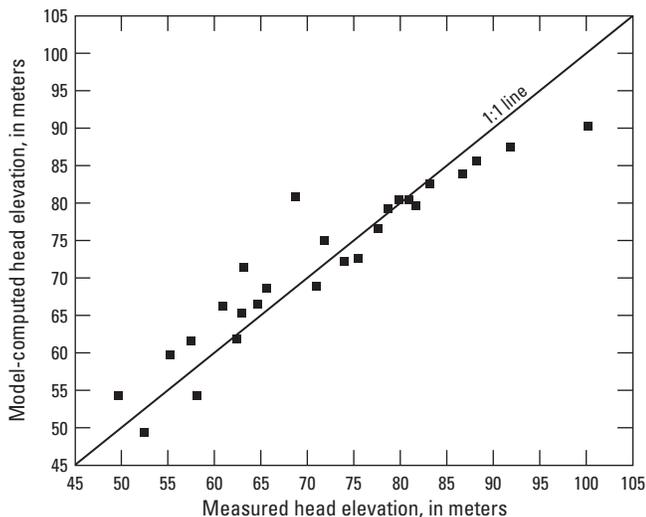


**Figure 6.8.** Hydraulic-conductivity and porosity zones for model layer 1, Pomperaug River Basin regional study area, Connecticut.

## Model-Computed Hydraulic Heads

A simple method of assessing model fit is to plot the model-computed hydraulic head values against the measured observations. For a perfect fit, all points should fall on the 1:1 diagonal line. Figure 6.9 presents a plot of the model-computed compared to the measured hydraulic heads for the study area and indicates a reasonable model fit. The average residual for the entire model is 0.43 m, and residuals range from -10.1 m to 8.2 m (range of 18.1 m). The RMSE for the entire model is 4.43 m, which is 11 percent of the range of head observations in the model (40.8 m). The standard deviation of the residuals is 4.50 m, and the SME is 0.88 m. The spatial distribution of model-computed hydraulic heads in layer 1 approximately parallels the land surface in upland areas, with the largest differences between model-computed and measured heads occurring near the contact between valley-fill sediments and bedrock (fig. 6.10). Factors that may cause differences between model-computed and measured heads include imprecise measuring-point elevations determined from topographic maps, spatial variation in saturated thicknesses and hydraulic conductivity not accounted for in the model, and imprecise recharge rates near the edge of the valley.

The simulated potentiometric surface for valley fill and analysis of basin-wide flow patterns indicate most ground water flows from upland areas toward the Pomperaug River at approximately right angles to the Pomperaug River consistent with the potentiometric surface for valley fill presented by Mazzaferro (1986a). For Bullet Hill Brook and its tributaries, potentiometric-surface data and model results indicate that ground-water flow approximately parallels the stream channels.



**Figure 6.9.** Relation between model-computed and measured hydraulic head, Pomperaug River Basin regional study area, Connecticut.

## Model-Computed Water Budget

The modeled-area water budget (table 6.4) indicates that areal recharge provides approximately 87 percent of the ground-water inflow, and about 13 percent of the ground-water inflow is from streams. Stream recharge is mostly from tributary streams where they cross valley-fill sediments (fig. 6.11). Stream losses also are apparent near the HV and WF wells. About 96 percent of ground-water discharge is to rivers, and about 4 percent of ground-water discharge is to wells. Recharge of wastewater discharged to ground water from septic tanks was not simulated but could account for an additional 1 percent of the inflow. Simulated streamflow at the outflow point for the basin is 161,000 m<sup>3</sup>/d, which is 46.2 cm/yr for the modeled area, or about 77 percent of average basin runoff of 59.9 cm/yr, as measured in the Pomperaug River at Southbury, Connecticut (Morrison and others, 2002).

A water budget for layer 1 in the area underlain by valley fill was determined using the program ZONEBUDGET (Harbaugh, 1990). This analysis indicated that more than one-half of the inflow to the valley-fill aquifer can be attributed

**Table 6.4.** Model-computed water budget for 1997–2001 average conditions, Pomperaug River Basin regional study area, Connecticut.

[m<sup>3</sup>/d, cubic meters per day]

Water-budget component	Flow rate (m <sup>3</sup> /d)	Percentage of inflow or outflow
<b>Modeled-area inflow</b>		
Recharge	169,000	87.2
Rivers	24,800	12.8
<b>TOTAL</b>	<b>193,800</b>	<b>100</b>
<b>Modeled-area outflow</b>		
Wells	7,650	3.9
Rivers	187,000	96.1
<b>TOTAL</b>	<b>194,650</b>	<b>100</b>
<b>Valley-fill aquifer inflow</b>		
Precipitation	45,500	34.2
Rivers	20,200	15.2
Lateral flow from layer 1	36,400	27.4
Vertical flow from layer 2	30,800	23.2
<b>TOTAL</b>	<b>132,900</b>	<b>100</b>
<b>Valley-fill aquifer outflow</b>		
Wells	7,100	5.3
Rivers	117,800	88.7
Lateral flow to layer 1	4,800	3.6
Vertical flow to layer 2	3,200	2.4
<b>TOTAL</b>	<b>132,900</b>	<b>100</b>

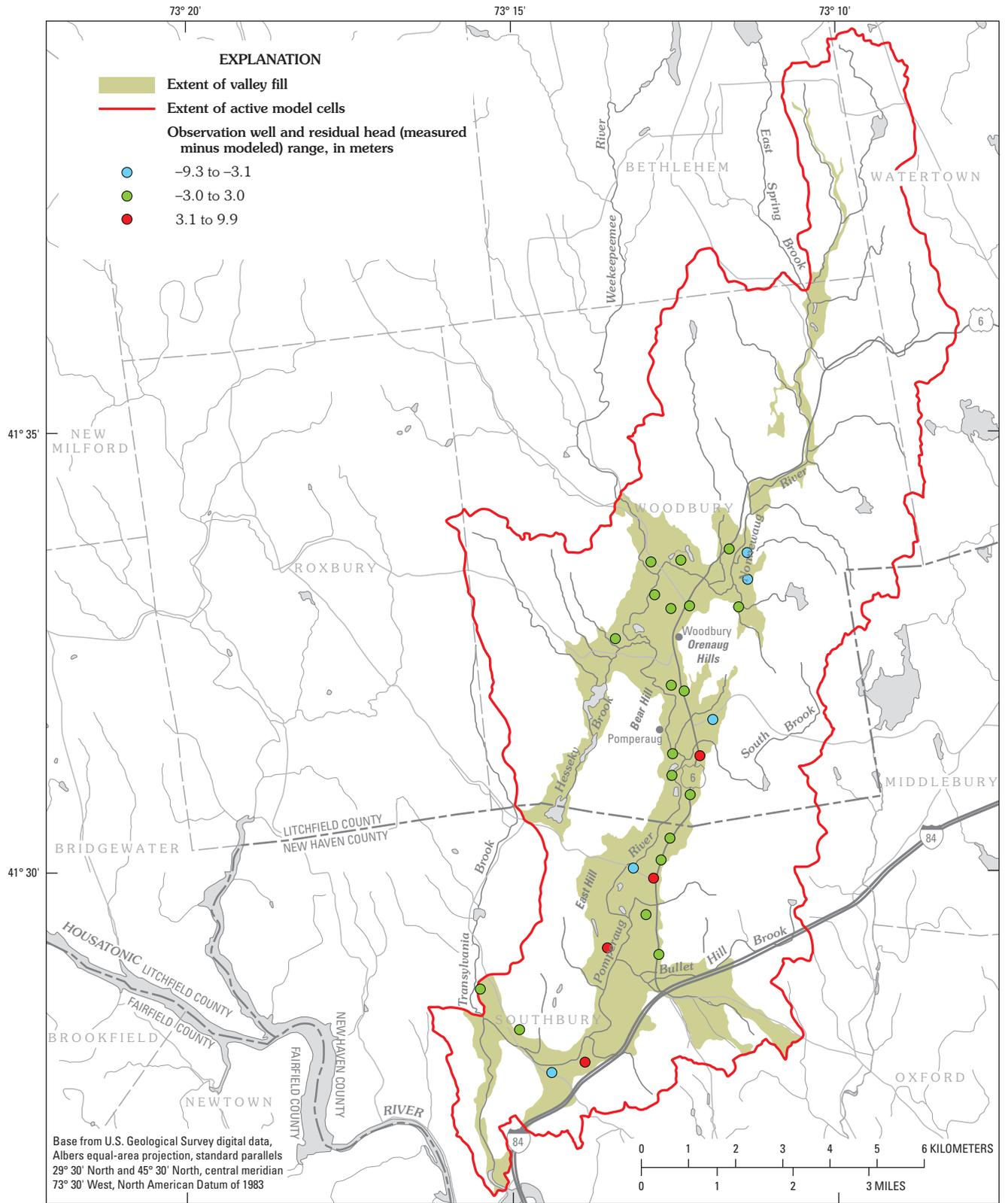


Figure 6.10. Observation points and head residuals, Pomperaug River Basin regional study area, Connecticut.

to upland runoff, which includes river leakage from tributary streams, lateral flow from layer 1 upland areas, and vertical leakage from layer 2 (table 6.4). The net contribution from uplands to valley fill is about 60 percent of the inflow, after adjusting for lateral and vertical outflows to layers 1 and 2 that eventually reenter the valley-fill aquifer. Discharge to wells is about 5 percent of the outflow for the valley-fill aquifer (table 6.4).

### Simulation of Areas Contributing Recharge to Public-Supply Wells

Areas contributing recharge to eight public-supply wells or well fields and traveltimes from recharge to discharge areas were simulated by particle-tracking using MODPATH (Pollock, 1994) and methods as described in Section 1 of this Professional Paper (fig. 6.11). A grid spacing of 30.5 m was used for the analysis of contributing areas to better identify flow paths for individual wells. Properties from the calibrated model were used for the finer grid. Porosity values were assigned as discussed in the section "Aquifer Hydraulic Properties." The model-computed areas contributing recharge represent advective ground-water flow and do not account for mechanical dispersion. Advection-dispersion transport simulations would likely yield larger areas contributing recharge than advective particle-tracking simulations because the effects of dispersion caused by aquifer heterogeneity would be included.

Several features of areas contributing recharge and zones of contribution that appear in figure 6.11 are considered noteworthy:

- For all wells completed in valley fill, the areas contributing recharge and zones of contribution extend upgradient into upland areas.
- Areas contributing recharge extend perpendicularly away from the Pomperaug River and its major tributaries reflecting that ground-water flow direction is perpendicular from upland areas toward the rivers.
- Areas contributing recharge can extend large distances from some wells. For example, the contributing area for WP extends approximately 3 km to the eastern model boundary and topographic divide.
- The contributing areas for WF and HV are larger than for other well sites because of larger pumping rates, as expected.
- Simulated losing reaches of streams occur within several of the contributing areas (fig. 6.11) indicating streams contribute recharge to public-supply wells.

An area-wide analysis indicated that traveltimes from recharge areas to wells ranged from less than 1 year to more than 275 years. The median traveltime to wells ranged from 0.2 to 25 years indicating the valley-fill aquifer is susceptible and vulnerable to contamination from overlying land uses.

Approximately 73 percent of the traveltimes were less than 10 years, 92 percent of the traveltimes were less than 25 years, 98 percent of the traveltimes were less than 45 years, and about 1 percent of the traveltimes were greater than 60 years.

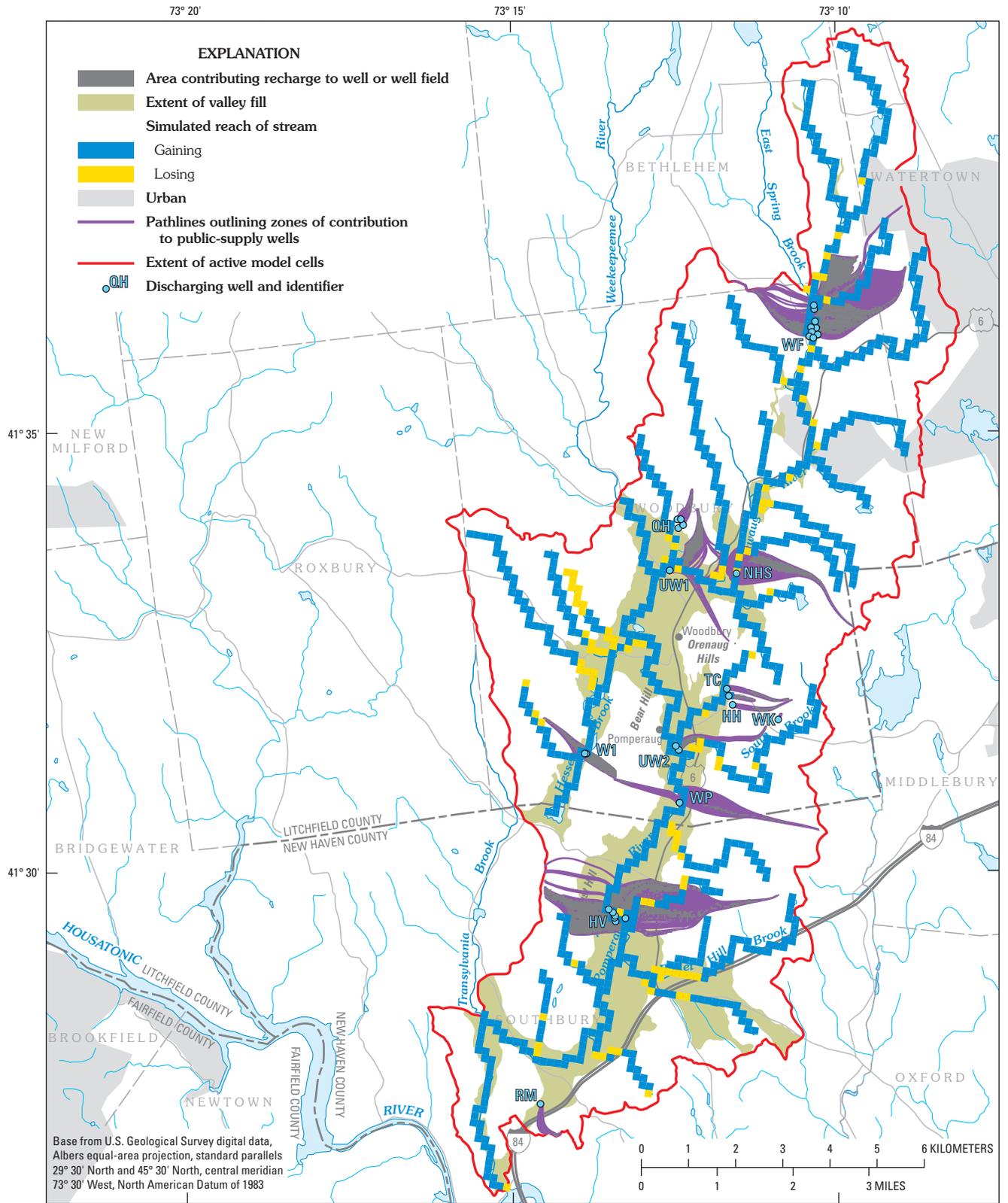
### Model Limitations and Uncertainties

The ground-water flow model for the Pomperaug River Basin regional study area was designed to delineate areas contributing recharge to public-supply wells, to help guide data collection, and to support future local modeling efforts. The model represents the general ground-water flow characteristics of the study area with some limitations including representation of steady-state conditions and the spatial distribution of aquifer parameters.

Water-level hydrographs and computed water budgets indicate the Pomperaug River valley-fill aquifer was generally in steady-state equilibrium for 1997–2001, although the data are not conclusive. Other uses of the model, such as assessing water-management alternatives or transient simulation of flow paths and water budgets, may not be appropriate without further calibration for transient conditions. Also, the model may not be appropriate for local-scale delineation of flow paths and rates, such as near local areas of ground-water contamination.

Particle-tracking simulations were done routinely during model calibration and indicated the contributing areas to wells did not change appreciably for the ranges of adjusted properties. Also, reduction of the grid size had a limited effect on contributing areas to wells except for the UW1 well, which received some water from the southeast for the finer grid (fig. 6.10) but not for the coarser grid. The observation that contributing areas did not change appreciably with variations in model characteristics adds support to the areas shown in figure 6.10. A formal uncertainty analysis, such as one described by Starn and others (2000), however, would be appropriate for delineation of wellhead-protection zones. The contributing areas to bedrock wells could change appreciably with refinements in bedrock properties and, particularly, recharge rates to till (Lyford and others, 2003).

Uncertainty is associated with simulated traveltimes because of uncertain porosity values and hydraulic conductivities of individual geologic units and the geometry of highly conductive zones, which were generalized in the model. In a steady-state model, changes to input porosity values do not change the area contributing recharge to a given well. Changes to input porosity values will change computed traveltimes from recharge to discharge areas in direct proportion to changes of effective porosity because there is an inverse linear relation between ground-water flow velocity and effective porosity and a direct linear relation between traveltime and effective porosity. For example, a one-percent decrease in porosity will result in a one-percent increase in velocity and a one-percent decrease in particle traveltime. A detailed sensitivity analysis of porosity distributions was beyond the scope of this study, although future work could compare simulated



**Figure 6.11.** Model-computed flow paths, areas contributing recharge to public-supply wells, and gaining and losing stream reaches, Pomperaug River Basin regional study area, Connecticut.

ground-water traveltimes to ground-water ages to more thoroughly evaluate effective porosity values.

The Pomperaug River Basin regional ground-water flow model uses justifiable aquifer properties and boundary conditions and provides a reasonable representation of ground-water flow conditions in the study area for 1997–2001. The model has been helpful for refining concepts about area-wide ground-water flow patterns and water budgets in the study area for the time period of interest but may not be suitable for long-term predictive simulations. This regional model provides a useful tool to evaluate aquifer vulnerability at a regional scale, to facilitate comparisons of ground-water traveltime between regional aquifer systems, and to guide future detailed investigations in the study area.

## References Cited

- Anderson, M.P., and Woessner, W.W., 1992, *Applied ground-water modeling*: New York, Academic Press, Inc., 381 p.
- Argus Interware, 1997, *Argus Numerical Environments and Mesh Maker User's Guide*: Jericho, N.Y., 463 p.
- Barlow, P.M., and Dickerman, D.C., 2001, Numerical-simulation and conjunctive-management models of the Hunt-Annaquatucket-Pettaquamscutt stream-aquifer system, Rhode Island: U.S. Geological Survey Professional Paper 1636, 88 p.
- Barton, G.J., Risser, D.W., Galeone, D.G., and Conger, R.W., 1999, Case study for delineating a contributing area to a water-supply well in a fractured crystalline-bedrock aquifer, Stewartstown, Pennsylvania: U.S. Geological Survey Water-Resources Investigations Report 99-4047, 38 p.
- Bent, G.C., 1995, Streamflow, ground-water recharge and discharge, and characteristics of surficial deposits in Buzzards Bay Basin, southeastern Massachusetts: U.S. Geological Survey Water-Resources Investigations Report 95-4234, 56 p.
- Bent, G.C., 1999, Streamflow, base flow, and ground-water recharge in the Housatonic River Basin, western Massachusetts and parts of eastern New York and northwestern Connecticut: U.S. Geological Survey Water-Resources Investigations Report 98-4232, 68 p.
- Bradbury, K.R., Muldoon, M.A., Zaporozec, A., and Levy, J., 1991, Delineation of wellhead protection areas in fractured rocks: U.S. Environmental Protection Agency, EPA 570/9-91-009, 144 p.
- Brown, C.J., and Chute, S.K., 2002, Arsenic concentrations in bedrock wells in Colchester, East Hampton, and Woodstock, Connecticut: U.S. Geological Survey Water-Resources Investigations Report 02-4135, 23 p.
- Cooper, H.H., Jr., and Jacob, C.E., 1946, A generalized graphical method for evaluating formation constants and summarizing well-field history: *American Geophysical Union Transactions*, v. 27, no. 4, p. 526–534.
- DeSimone, L.A., Walter, D.A., Eggleston, J.R., and Nimiroski, M.T., 2002, Simulation of ground-water flow and evaluation of water-management alternatives in the Upper Charles River Basin, eastern Massachusetts: U.S. Geological Survey Water-Resources Investigations Report 02-4234, 94 p.
- Dickerman, D.C., Kliever, J.D., and Stone, J.R., 1997, Hydrogeology, water quality, and simulation of ground-water development alternatives in the Usquepaug-Queen ground-water reservoir, Southern Rhode Island: U.S. Geological Survey Water-Resources Investigations Report 97-4126, 48 p.
- Dickerman, D.C., Trench, E.C.T., and Russell J.P., 1990, Hydrogeology, water quality, and ground-water development alternatives in the lower Wood River ground-water reservoir, Rhode Island: U.S. Geological Survey Water-Resources Investigations Report 89-4031, 109 p.
- Ellis, E.E., 1909, Ground water in crystalline rocks of Connecticut, *in* Gregory, H.E., ed., *Underground water resources of Connecticut*: U.S. Geological Survey Water-Supply Paper 232, p. 54–103.
- Fetter, C.W., 1994, *Applied hydrogeology* (3rd ed.): Englewood Cliffs, N.J., Prentice-Hall, Inc., 691 p.
- Gates, R.M., 1954, Bedrock geology of the Woodbury quadrangle: Connecticut Geological and Natural History Survey Quadrangle Report 3, 23 p., scale 1:31,680.
- Gates, R.M., 1959, Bedrock geology of the Roxbury quadrangle, Connecticut: U.S. Geological Survey Geologic Quadrangle Map GQ-121, scale 1:24,000.
- Gburek, W.J., Folman, G.J., and Urban, J.B., 1999, Field data and ground-water modeling in a layered fractured aquifer: *Ground Water*, v. 37, no. 2, p. 175–184.
- Grady, S.J., and Weaver, M.F., 1988, Preliminary appraisal of the effects of land use on water quality in stratified-drift aquifers in Connecticut—U.S. Geological Survey Toxic Waste-Ground-Water Contamination Program: U.S. Geological Survey Water-Resources Investigations Report 87-4005, 41 p.
- Harbaugh, A.W., 1990, A computer program for calculating subregional water budgets using results from the U.S. Geological Survey modular three-dimensional ground-water flow model: U.S. Geological Survey Open-File Report 90-392, 46 p.

- Harbaugh, A.W., Banta, E.R., Hill, M.C., McDonald, M.G., 2000, MODFLOW-2000, the U.S. Geological Survey modular ground-water models—User guide to modularization concepts and the ground-water flow process: U.S. Geological Survey Open-File Report, 00–92, p. 121.
- Heath, R.C., 1989, Basic ground-water hydrology: U.S. Geological Survey Water-Supply Paper 2220, 84 p.
- Hovey, E.O., 1890, The oil well of Southbury, Connecticut: *Scientific American*, v. 62, p. 275.
- Kontis, A.L., Randall, A.D., and Mazzaferro, D.L., 2004, Regional hydrology and simulation of flow of stratified drift aquifers in the glaciated Northeastern United States: U.S. Geological Survey Professional Paper 1415–C, 156 p.
- Lyford, F.P., Carlson, C.S., and Hansen, B.P., 2003, Delineation of water sources for public-supply wells in three fractured-bedrock aquifer systems in Massachusetts: U.S. Geological Survey Water-Resources Investigations Report 02–4290, 113 p.
- Lyford, F.P., and Cohen, A.J., 1988, Estimation of water available for recharge to sand and gravel aquifers in the glaciated Northeastern United States, *in* Randall, A.D., and Johnson, A.I., eds., 1988, Regional aquifer systems of the United States—The northeast glacial aquifers: American Water Resources Association Monograph Series no. 11, p. 37–61.
- Masterson, J.P., Walter, D.A., and Savoie, Jennifer, 1997, Use of particle tracking to improve numerical model calibration and to analyze ground-water flow and contaminant migration, Massachusetts Military Reservation, western Cape Cod, Massachusetts: U.S. Geological Survey Water-Supply Paper 2482, 50 p.
- Mazzaferro, D.L., 1986a, Ground-water availability and water quality in Southbury and Woodbury, Connecticut: U.S. Geological Survey Water-Resources Investigations Report 84–4221, 105 p.
- Mazzaferro, D.L., 1986b, Depth to bedrock, depth to the water table, and classification of unconsolidated materials above the water table in stratified-drift areas of part of the Pomperaug River valley, Southbury and Woodbury, Connecticut: U.S. Geological Survey Miscellaneous Investigations Series Map I-1690, scale 1:24,000.
- Mazzaferro, D.L., Handman, E.H., and Thomas, M.P., 1979, Water resources inventory of Connecticut, part 8, Quinnipiac River basin: Connecticut Water Resources Bulletin, no. 27, 88 p.
- Meinzer, O.E., and Stearns, N.D., 1929, A study of ground water in the Pomperaug basin, Connecticut, with special reference to intake and discharge: U.S. Geological Survey Water-Supply Paper 597–B, p. 73–146.
- Melvin, R.L., Stone, B.D., Stone, J.R., and Trask, J.J., 1992, Hydrogeology of thick till deposits in Connecticut: U.S. Geological Survey Open-File Report 92–43, 49 p.
- Morris, D.A., and Johnson, A.I., 1967, Summary of hydrologic and physical properties of rock and soil materials, as analyzed by the Hydrologic Laboratory of the U.S. Geological Survey, 1948–60: U.S. Geological Survey Water-Supply Paper 1839–D, 42 p.
- Morrison, Jonathan, Provencher, P.L., Martin, J.W., and Norris, J.R., 2002, Water resources data, Connecticut, water year 2001: U.S. Geological Survey Water-Data Report CT-01–1, 353 p.
- Morrissey, D. J., 1983, Hydrology of the Little Androscoggin River valley aquifer, Oxford County, Maine: U.S. Geological Survey Water-Resources Investigations 83–4018, 79 p.
- Morrissey, D.J., Randall, A.D., and Williams, J.H., 1988, Upland runoff as a major source of recharge to stratified-drift aquifers in the glaciated Northeast, *in* Randall, A.D., and Johnson, A.I., eds., 1988, Regional aquifer systems of the United States—The northeast glacial aquifers: American Water Resources Association Monograph Series no. 11, p. 17–36.
- Mullaney, J.R., and Grady, S.J., 1997, Hydrogeology and water quality of a surficial aquifer underlying an urban area, Manchester, Connecticut: U.S. Geological Survey Water-Resources Investigations Report 97–4195, 40 p.
- Pessl, Fred, Jr., 1970, Surficial geologic map of the Woodbury quadrangle, Litchfield and New Haven Counties, Connecticut: U.S. Geological Survey Geologic Quadrangle Map GQ-896.
- Pollock, D.W., 1994, User's guide for MODPATH/MODPATH-PLOT, Version 3—A particle tracking post-processing package for MODFLOW, the U.S. Geological Survey finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 94–464, accessed Feb. 6, 2007 at <http://water.usgs.gov/nrp/gwsoftware/modpath41/modpath41.html>
- Prudic, D.E., 1989, Documentation of a computer program to simulate stream-aquifer relations using a modular, finite-difference, ground-water flow model: U.S. Geological Survey Open-File Report 88–729, 113 p.
- Randall, A.D., 1996, Mean annual runoff, precipitation, and evapotranspiration in the glaciated Northeastern United States, 1951–1980: U.S. Geological Survey Open-File Report 96–395, 2 plates.
- Randall, A.D., 2001, Hydrogeologic framework of stratified-drift aquifers in the glaciated Northeastern United States: U.S. Geological Survey Professional Paper 1415–B, 179 p.

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- Randall, A.D., Francis, R.M., Frimpter, M.H., and Emery, J.M., 1988, Region 19, Northeastern Appalachians, *in* Back, W., Rosenshein, J.S., and Seaber, P.R., eds., *Hydrogeology: Boulder, Colorado, Geological Society of America, The geology of North America*, v. O-2, p. 177-187.
- Rodgers, John (compiler), 1985, *Bedrock geological map of Connecticut: Connecticut Geological and Natural History Survey, Natural Resources Atlas Series Map, 2 sheets, scale 1:125,000.*
- Rogers, R.J., 1989, *Geochemical comparison of ground water in areas of New England, New York, and Pennsylvania: Ground Water*, v. 27, no. 5, p. 690-712.
- Rutledge, A.T., 1993, *Computer programs for describing the recession of ground-water discharge and for estimating mean ground-water recharge and discharge from streamflow records: U.S. Geological Survey Water-Resources Investigations Report 93-4121, 45 p.*
- Rutledge, A.T., 1997, *Model-estimated ground-water recharge and hydrograph of ground-water discharge to a stream: U.S. Geological Survey Water-Resources Investigations Report 97-4253, 29 p.*
- Rutledge, A.T., 1998, *Computer programs for describing the recession of ground-water discharge from streamflow records-update: U.S. Geological Survey Water-Resources Investigations Report 98-4148, 43 p.*
- Scott, R.B., 1974, *The bedrock geology of the Southbury quadrangle, Connecticut: Connecticut Geological and Natural History Survey Quadrangle Report 30, 63 p., scale 1:24,000.*
- Stanley, R.S., and Caldwell, K.G., 1976, *The bedrock geology of the Newtown Quadrangle; Connecticut Geological and Natural History Survey, Quadrangle Report 33, 43 p., scale 1:24,000.*
- Starn, J.J., Stone, J.R., and Mullaney, J.R., 2000, *Delineation and analysis of uncertainty of contributing areas to wells at the Southbury Training School, Southbury, Connecticut: U.S. Geological Survey Water-Resources Investigations Report 00-4158, 53 p.*
- Stone, J.R., Schafer, J.P., London, E.H., DeGiacome-Cohen, Mary, Lewis, R.S., and Thompson, W.B., 1998, *Quaternary geologic map of Connecticut and Long Island Sound Basin: U.S. Geological Survey Open-File Report 98-371, 69 p.*
- Tepper, D.H., Morrissey, D.J., and Johnson, C.D., 1990, *Hydrogeology, water quality, and effects of increased municipal pumpage of the Saco River valley glacial aquifer—Bartlett, New Hampshire to Fryeburg, Maine: U.S. Geological Survey Water-Resources Investigations Report 88-4179, 113 p., 6 pls.*
- Tiedeman, C.R., Goode, D.J., and Hsieh, P.A., 1997, *Numerical simulation of ground-water flow through glacial deposits and crystalline bedrock in the Mirror Lake area, Grafton County, New Hampshire: U.S. Geological Survey Professional Paper 1572, 50 p.*
- Thomas, M.A., Hollis, J.N., Rothney, L.M., Toal, B.F., and Dupuy, C.J., 1988, *Correlating radon distribution with geology and areal radioactivity in Connecticut: Northeastern Environmental Science*, v. 7, p. 10.
- Thomas, M.A. and McHone, N.W., 1997, *Indoor radon potential map of Connecticut: Connecticut Departmental of Environmental Protection.*
- Walsh, G.J., 2001a, *Bedrock geology in the vicinity of the Rockland Avenue Well Site, Maynard, Massachusetts: U.S. Geological Survey Open File Report 01-354, 15 p.*
- Walsh, G.J., 2001b, *Bedrock geology in the vicinity of the Knowles and Andreas Well Sites, West Newbury, Massachusetts: U.S. Geological Survey Open File Report 01-353, 14 p.*
- Walsh, G.J., 2002, *Bedrock geology in the vicinity of the Leicester well site, Paxton, Massachusetts: U.S. Geological Survey Open-File Report 02-433, 19 p.*
- Warner, K.L., and Arnold, T.L., 2005, *Framework for regional synthesis of water-quality data for the glacial aquifer system in the United States: U.S. Geological Survey Scientific-Investigations Report 2005-5223, 6 p.*
- Williams, J.H., and Morrissey, D.J., 1996, *Recharge of valley-fill aquifers in the glaciated northeast from upland runoff in Subsurface fluid-flow (ground-water and vadose zone) modeling, Joseph D. Ritchey and James O. Rumbaugh, eds.: ASTM STP 1288, , American Society for Testing and Materials, p. 97-113.*
- Winston, R.B., 2000, *Graphical user interface for MODFLOW, version 4: U.S. Geological Survey Open-File Report 00-315, 27 p.*