USGS
science for a changing world

Prepared in cooperation with the
New York State Department of Environmental Conservation

Hydrogeology of the West Branch Delaware River Basin, Delaware County, New York

Scientific Investigations Report 2013–5025

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

Cover. Groundwater discharging from bedrock fractures exposed in a roadcut of Catskill Mountain Series rocks (upper Walton Formation), Ulster County, New York. Deeper springs emerging from fractures or bedding planes in bedrock are used extensively throughout the Catskill Mountain region for domestic and municipal water supplies, and provide a major contribution to the base flow of streams in the region. Photo by Jason Zatorsky, U.S. Geological Survey, January 2003.

Hydrogeology of the West Branch Delaware River Basin, Delaware County, New York

By Richard J. Reynolds

Prepared in cooperation with the
New York State Department of Environmental Conservation

Scientific Investigations Report 2013–5025

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

U.S. Department of the Interior
SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2013

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment, visit http://www.usgs.gov or call 1–888–ASK–USGS.

For an overview of USGS information products, including maps, imagery, and publications, visit http://www.usgs.gov/pubprod

To order this and other USGS information products, visit http://store.usgs.gov

Suggested citation:
Reynolds, R.J., 2013, Hydrogeology of the West Branch Delaware River basin, Delaware County, New York: U.S. Geological Survey Scientific Investigations Report 2013–5025, 26 p., http://pubs.usgs.gov/sir/2013/5025/.

Contents

Figures

Tables

Conversion Factors and Datum

Inch/Pound to SI

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)
cubic foot per second (ft^3/s)	28.32	foot per second (m^3/s)
cubic foot per second per square mile [(ft^3/s)/mi^2]	0.01093	cubic meter per second per square kilometer [(m^3/s)/km^2]
gallon per minute (gal/min)	0.06309	liter per second (L/s)
gallon per day per foot (gal/d/ft)	0.0001437	liter per second per meter (L/s/m)
gallon per day per square mile [(gal/d)/mi^2]	0.001461	cubic meter per day per square kilometer [(m^3/d)/km^2]
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
million gallons per day (Mgal/d)	3,785	cubic meter per day (m^3/d)
million gallons per day per square mile [(Mgal/d)/mi^2]	1,461	cubic meter per day per square kilometer [(m^3/d)/km^2]
	Specific capacity	
gallon per minute per foot [(gal/min)/ft)]	0.2070	liter per second per meter [(L/s)/m]
	Hydraulic conductivity*	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Hydraulic gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
	Transmissivity**	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83) and the North American Datum of 1927 (NAD 27).

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

*Hydraulic conductivity: The standard unit for hydraulic conductivity is cubic foot per day per square foot of aquifer cross-sectional area ($ft^3/d/ft^3$). In this report, the mathematically reduced form, feet per day (ft/d), is used for convenience.

**Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [(ft^3/d)/ft^2]ft. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

Abbreviations

GIS	geographic information system
NRCS	Natural Resources Conservation Service
NYSDEC	New York State Department of Environmental Conservation
USGS	U.S. Geological Survey

Hydrogeology of the West Branch Delaware River Basin, Delaware County, New York

By Richard J. Reynolds

Abstract

In 2009, the U.S. Geological Survey, in cooperation with the New York State Department of Environmental Conservation, began a study of the hydrogeology of the West Branch Delaware River (Cannonsville Reservoir) watershed. There has been recent interest by energy companies in developing the natural gas reserves that are trapped within the Marcellus Shale, which is part of the Hamilton Group of Devonian age that underlies all the West Branch Delaware River Basin. Knowing the extent and thickness of stratified-drift (sand and gravel) aquifers within this basin can help State and Federal regulatory agencies evaluate any effects on these aquifers that gas-well drilling might produce. This report describes the hydrogeology of the 455-square-mile basin in the southwestern Catskill Mountain region of southeastern New York and includes a detailed surficial geologic map of the basin.

Analysis of surficial geologic data indicates that the most widespread surficial geologic unit within the basin is till, which is present as deposits of ablation till in major stream valleys and as thick deposits of lodgment till that fill upland basins. Till and colluvium (remobilized till) cover about 89 percent of the West Branch Delaware River Basin, whereas stratified drift (outwash and ice-contact deposits) and alluvium account for 8.9 percent. The Cannonsville Reservoir occupies about 1.9 percent of the basin area. Large areas of outwash and ice-contact deposits occupy the West Branch Delaware River valley along its entire length. These deposits form a stratified-drift aquifer that ranges in thickness from 40 to 50 feet (ft) in the upper West Branch Delaware River valley, from 70 to 140 ft in the middle West Branch Delaware River valley, and from 60 to 70 ft in the lower West Branch Delaware River valley.

The gas-bearing Marcellus Shale underlies the entire West Branch Delaware River Basin and ranges in thickness from 600 to 650 ft along the northern divide of the basin to 750 ft thick along the southern divide. The depth to the top of the Marcellus Shale ranges from 3,240 ft along the northern basin divide to 4,150 ft along the southern basin divide.

Yields of wells completed in the aquifer are as high as 500 gallons per minute (gal/min). Springs from fractured sandstone bedrock are an important source of domestic and small municipal water supplies in the West Branch Delaware River Basin and elsewhere in Delaware County. The average yield of 178 springs in Delaware County is 8.5 gal/min with a median yield of 3 gal/min. An analysis of two low-flow statistics indicates that groundwater contributions from fractured bedrock compose a significant part of the base flow of the West Branch Delaware River and its tributaries.

Introduction

The West Branch Delaware River (Cannonsville Reservoir) watershed occupies a drainage area of approximately 455 square miles (mi^2) in the Catskill Mountain region of southeastern New York. The watershed encompasses all but 1 mi^2 of the West Branch Delaware River Basin, as measured at the U.S. Geological Survey (USGS) streamgaging station at Stilesville (01425000) about 17.8 miles (mi) upstream from the confluence of the West and East Branch Delaware Rivers at Hancock, New York. In this report, the West Branch Delaware River Basin refers to the 455 mi^2 of the basin that lies upstream from the Cannonsville Reservoir and does not include the 211 mi^2 between the reservoir and the downstream confluence of the West and East Branch Delaware Rivers. The location of the West Branch Delaware River Basin is shown in figure 1.

The West Branch Delaware River valley, upstream of the Cannonsville Reservoir, extends for 59 mi from the Cannonsville Reservoir Dam to the river's headwaters near Stamford, N.Y., and supplies municipal groundwater to the villages of Delhi, Hobart, Stamford, and Walton (fig. 1) and to the Bloomville Water District, collectively serving a population of more than 11,000 people (New York State Department of Health, 1982). The stratified drift within this valley consists of outwash and ice-contact deposits of sand, gravel, silt, and clay, and fine-grained lacustrine deposits, locally mantled by postglacial alluvium. The outwash and ice-contact deposits together constitute the principal stratified-drift (sand and gravel) aquifer in this valley and may reach thicknesses of up to 140 feet (ft) in places, such as near Hawleys, N.Y. In the lowest reach of the valley, some of the valley fill consists of low permeability lacustrine silt and clay, which are the result

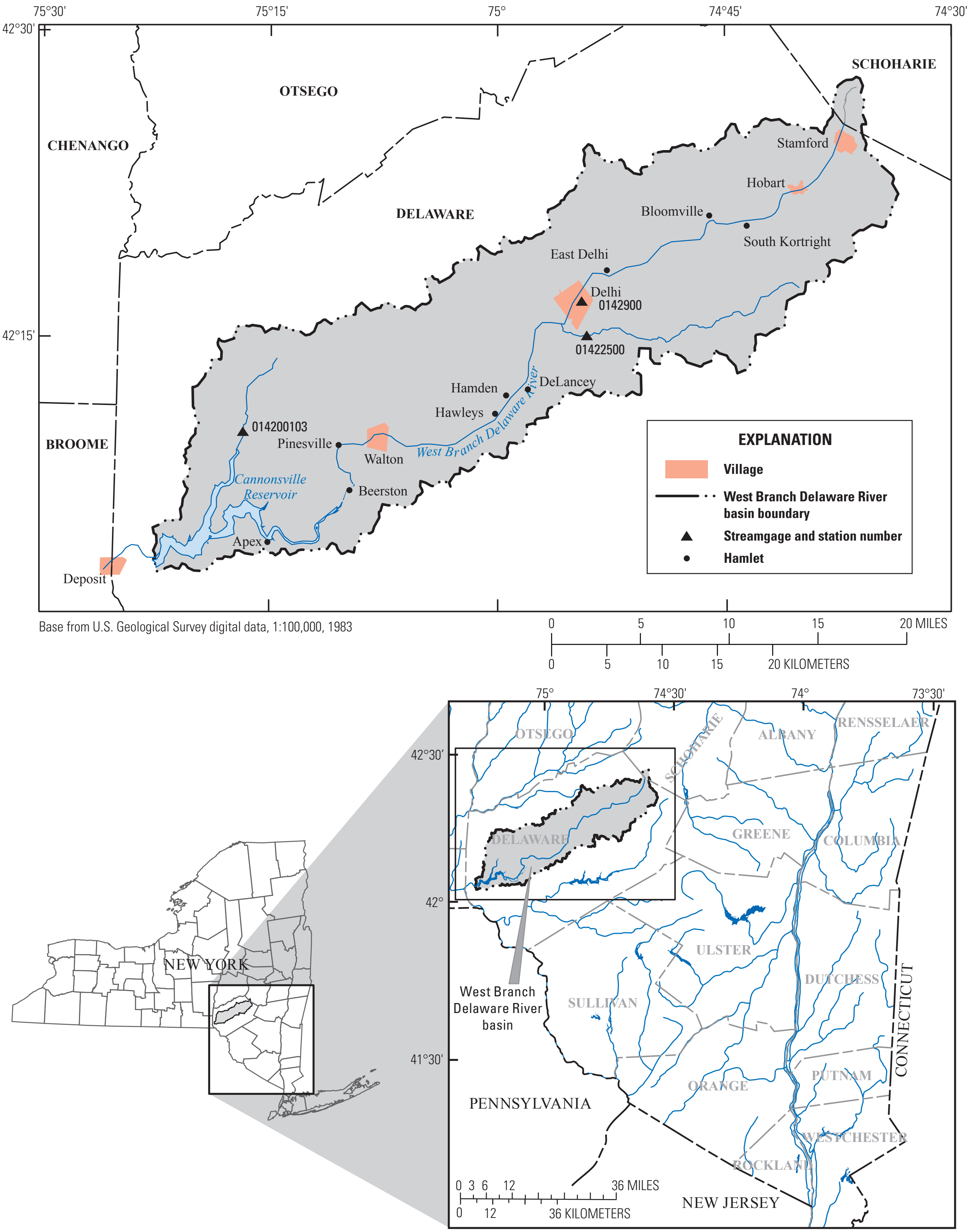

Figure 1. The location of the West Branch Delaware River Basin in southeastern New York.

of remnant glacial lakes. In other areas, permeable ice-contact sand and gravel are buried beneath large thicknesses of silt and clay or till, forming confined aquifers. Each of these hydrogeologic situations has specific implications for the availability of groundwater for public supply. In addition, groundwater in the water-table aquifer is hydraulically connected to the river within the valley and discharges to the river to sustain base flow during periods of little or no precipitation.

Recently, there has been interest by energy companies in developing the natural gas reserves that are trapped within the Marcellus Shale, which is part of the Hamilton Group of Devonian age that underlies all of the West Branch Delaware River Basin. Concern has been expressed by local interest groups that gas-well drilling might have adverse effects on both the sand and gravel and the bedrock aquifers that overlie the Marcellus Shale, including contamination of overlying aquifers with hydrocarbons, depletion of groundwater in productive aquifers used to supply hydrofracturing operations with subsequent effect on nearby domestic wells, and possible groundwater contamination from specialized drilling fluids. Knowing the character, extent, and thickness of stratified-drift aquifers within this basin can help State and Federal regulatory agencies in the evaluation of potential effects on these aquifers that gas-well drilling might produce.

In 2009, the U.S. Geological Survey (USGS), in cooperation with the New York State Department of Environmental Conservation (NYSDEC), began a study of the hydrogeology of the West Branch Delaware River Basin (Cannonsville Reservoir watershed) that entailed delineating the surficial geology of the basin, describing the extent and thickness of the stratified drift aquifer within the valley, and describing the general hydrogeology of the underlying bedrock units and their relation and effect on stream base flow.

Purpose and Scope

The primary objective of this study was to define the hydrogeology of the valley-fill aquifer system in the West Branch Delaware River valley, above the Cannonsville Reservoir. This was accomplished through the delineation of surficial geologic units within the basin, compilation of well and test-hole data from several databases (including the NYSDEC well database), and subsequent creation of geographic information system (GIS) datasets of surficial geology, locations of wells and test holes, and bedrock geology.

The mapped area consists of all or part of eighteen 7.5-minute quadrangles and covers an area of 455 mi^2. The map was derived from several sources: (1) digital soils maps of Delaware County produced by the Natural Resources Conservation Service (NRCS) of the U.S. Department of Agriculture, (2) maps and illustrations from unpublished doctoral dissertations by Kirkland (1973) and Ozvath (1985); and (3) unpublished reconnaissance-level surficial geologic maps at 1:62,500 scale, prepared during a previous USGS study (Soren, 1963) of the groundwater resources of Delaware County (Julian Soren, U.S. Geological Survey, unpub. maps, 1958). Surficial geology was superimposed on topography mapped at 1:24,000 scale; the mapping included upland areas that are adjacent and tributary to the main valley-fill aquifers

This report (1) describes the distribution and character of surficial geologic units throughout the West Branch Delaware River Basin, (2) outlines the deglacial chronology that led to the deposition of successive stratified-drift units in the main valley, (3) discusses the approximate thickness and character of stratified-drift aquifers within three reaches of the West Branch Delaware River, (4) describes the general stratigraphy and hydrogeology of the bedrock that underlies the basin, and (5) gives available information on the thickness and depth to the Marcellus Shale that underlies the entire basin.

Previous Studies

Several investigators have studied various hydrologic and geologic aspects of the Delaware River Basin in New York. Rich (1935) studied the surficial geology of the western and central Catskill Mountains, including the eastern third of the West Branch Delaware River Basin, and reported evidence of two distinct drift sheets, which he termed “early” and “late” Wisconsinan. Later investigations of the glacial geology within this basin included doctoral dissertations by Kirkland (1973) and Ozvath (1985). Kirkland’s study encompassed most of the West Branch Delaware River Basin, whereas Ozvath’s study included only the westernmost part of the basin.

Investigations by the USGS in the 1950s and early 1960s, in cooperation with the New York State Department of Conservation (superceded by NYSDEC in 1970), produced a report on the groundwater resources of Delaware County (Soren, 1963), which includes the West Branch Delaware River Basin. Geotechnical and engineering studies conducted by the New York City Board of Water Supply, in conjunction with the planned construction of the Cannonsville Reservoir, were summarized in Fluhr (1953) and Fluhr and Terenzio (1984). N.M.Perlmutter and E.H. Salvas (U.S. Geological Survey, written commun., 1957) described various aspects of groundwater in the New York part of the Delaware River Basin; their findings were later incorporated into a larger USGS study of the entire Delaware River Basin conducted in the early 1960s by Parker and others (1964). As part of that same basinwide USGS study, Hely and Olmsted (1963) investigated the relation between low-flow statistics and watershed characteristics in the entire Delaware River Basin. A comparison study of Delaware and Susquehanna River Basin streams by Coates (1971) investigated the relation of bedrock type and joint spacing, extent of valley-fill stratified sediments, and several geomorphic indices to stream base flow, and provided streamflow and low-flow statistics for all gaged streams in the Delaware River Basin in New York. Most recently, Reynolds (2004) delineated the surficial geology of the Pepacton Reservoir watershed in the East Branch Delaware River Basin and observed that the magnitude of base flows in this basin correlated positively with the extent and massiveness of sandstone relative to shale and siltstone bedrock, as measured by Coates (1971), but—contrary to the results of studies elsewhere in the glaciated Northeast—did not correlate with the extent of stratified valley-fill sediments. Reynolds (2000) also delineated the surficial geology of the Beaver Kill Basin to the south and noted that 90-percent flow duration was substantially larger and base-flow recessions generally more sustained in this watershed than elsewhere in the Delaware River Basin, which could be attributed to a larger water input from precipitation and to the underlying massive sandstone, which contains extensive water-bearing fractures.

Hydrogeology

The thickness, type, and areal extent of surficial geologic units within the West Branch Delaware River Basin are the direct result of the mode of deglaciation and largely determine the groundwater productivity and storage in the valley-fill aquifer.

Deglaciation of the West Branch Delaware River Basin

The style of deglaciation that occurred in the West Branch Delaware River Basin resulted in the deposition of large volumes of sand and gravel both as ice-contact features, and as valley-train outwash throughout the entire 59-mi-long valley from Stamford to Deposit, N.Y. Ice retreat in the valley of the West Branch Delaware River was characterized by a series of ice-tongue detachments that resulted in six zones of stagnant ice (Ozvath, 1985). These stagnant-ice zones ranged in length from 10 to 15 mi each, and together indicate six fluvial morphosequences (Koteff, 1974), in which a complete morphosequence consists of outwash grading upstream to pitted outwash, and then to kame moraine or kame terrace. Deglaciation in the more sinuous East Branch Delaware River to the south, in contrast, occurred through the ablation of stagnant-ice masses, which in turn resulted in a succession of proglacial lakes in the lower reaches of the East Branch Delaware River valley. In these morphosequences, a kame moraine marks the end position of a detached ice tongue, whereas upstream kame terraces were constructed by meltwater streams flowing between the melting ice tongue and the valley wall. These morphosequences range from 10 to 15 mi in length and their depositional features were formed at both the end and valley-side margins of an ice tongue that had become detached from the main ice sheet and began to stagnate (melt). Kirkland (1979) identified six of these well-defined morphosequences in the West Branch Delaware River valley from Deposit to Stamford. Although much of the evidence, especially kame moraines, for these six morphosequences have been either eroded or buried by subsequent deposition, a study by Ozvath (1985) identified several kame moraines in the West Branch Delaware River valley that serve to locate former ice margins and thus corroborate Kirkland's deglaciation model. Ozvath (1985) and Kirkland (1979) agreed that, with few exceptions, all the stratified drift exposures in the West Branch Delaware River valley indicate continuous deposition by glacial meltwater flowing downvalley (southwest). The distribution of outwash and ice-contact deposits (plate 1) supports this finding, as do the logs of wells in the valley that consistently show coarse-grained sand and gravel down to bedrock in places along the entire 59-mi stretch of valley. There are a few depositional features known as kame deltas, however, which indicate that small, short-lived proglacial lakes existed in several places along the West Branch Delaware River. These lakes typically formed between a detached ice block located at a sharp curve or narrowing of the river valley, causing a temporary lake to form and extend upstream to the retreating ice tongue. Ozvath (1985) identified a kame delta about 1 mi north of Delhi and another pair 2 mi southwest of Delhi that give evidence for temporary glacial lakes in this reach. One lake level stood at about 1,400 ft and stretched from a dam of stagnant ice at Delhi about 2 mi upstream to East Delhi, where the lake level is also seen in a deltaic complex. The existence of this lake is supported by the logs of two wells (D–2208 and D–1442) in this reach that show thicknesses of about 60 to 75 ft of lacustrine silt within the valley fill. Further downvalley two kame deltas near Pinesville and one on the south side of the sharp "S" bend in the river southwest of Walton, record a temporary proglacial lake level of 1,280 ft (Ozvath, 1985). The ice dam that produced this lake was most likely located in the sharp "S" bend southwest of Walton. The logs of two wells (D–102 and D–175) in Walton and one (D–1337) south of Walton at Beerston, N.Y., show thicknesses of lacustrine silt and clay ranging from 40 to more than 100 ft, thus confirming the existence of this short-lived proglacial lake.

Ozvath and Coates (1986) have correlated two of Kirkland's (1973) six ice-marginal positions in the West Branch Delaware River valley to nearby ice-marginal positions in the Susquehanna River valley, which have radiocarbon dates associated with them. These radiocarbon dates place, by inference, the ice tongue in the West Branch Delaware River valley at Walton approximately 16,650 years before present (B.P.; plus or minus 1,800 years) and at Delhi approximately 14,860 years B.P (plus or minus 800 years). These data therefore suggest that the rate of retreat of the ice tongue along the central reach of the West Branch Delaware River valley was extremely slow, taking on the order of 1,800 years to retreat the 16 mi from Walton to Delhi. This pace would have allowed plenty of time for the small localized proglacial lakes to accumulate up to 100 ft of fine-grained sediment that are now evident in the several well logs mentioned above.

Surficial Geology

A primary objective of this study was to produce a generalized surficial geologic map of the West Branch Delaware River Basin above the Cannonsville Reservoir Dam that can be used to identify the location and extent of stratified-drift aquifers within the drainage area of the Cannonsville Reservoir. The surficial geologic map (plate 1) includes all or part of eighteen 7.5-minute quadrangles and represents an area of 455 mi^2. The map is based on the interpretation of surficial units derived from three primary sources: (1) digital soils maps of Delaware County produced by the NRCS in Walton; (2) plates and illustrations in doctoral dissertations by Kirkland (1973) and Ozvath (1985); and (3) unpublished reconnaissance-level surficial geologic maps at 1:62,500 scale prepared as part of a previous USGS study by Soren (1963). To compile this map, an analysis of the GIS coverage of NRCS soils units for the study area showed that there were 154 individual soil types within the basin. These 154 soil types were used to identify their parent materials, on the basis of the soils descriptions given in the NRCS soils report. The individual soil types were each assigned a color based on its assigned parent material and then aggregated by common parent material in a GIS coverage to identify 11 surficial geologic map units: alluvium, alluvium over outwash, alluvial fans, artificial fill, kame sand and gravel, outwash and (or) kame sand and gravel (undifferentiated), outwash sand and gravel, peat and muck, exposed bedrock, till and thick till, and till and (or) colluvium (undifferentiated). The map units were plotted as overlays to 1:24.000-scale topographic maps within the basin and were checked to determine whether the unit contacts generally conformed to topography. In addition, morphostratigraphic units delineated either by Kirkland (1973) or by Ozvath (1985) in valley sections were compared with those derived from the soils units and with field notes and observations (Julian Soren, U.S. Geological Survey, unpub. maps, 1958). Generally, the contacts of surficial geologic units as delineated from the soils data conformed very well to the topography. Areas identified as kame sand and gravel plotted where they were expected to be, that is, on valley-side terraces. Areas of valley train outwash, alluvium, and alluvial fans were also well delineated from the soils data. Similarly, areas of thick lodgment till (greater than 5 ft) in upland valleys or colluvium were located in upland tributaries and on the sides of steep valley walls, where they would also be expected. The soils-derived surficial geologic map in this report is in good agreement with similar mapping of surficial geologic units by Kirkland (1979) and Ozvath (1985) and compares well with unpublished field mapping (Julian Soren, U.S. Geological Survey, unpub. maps, 1958). In some cases, the exact origin of a morphostratigraphic unit could not be determined from the soils data; for example, whether a sand and gravel unit was derived from ice-contact material or from outwash. Similarly, the soils data could sometimes not be used to help differentiate between areas of till and colluvium (remobilized till). The ambiguities of these two mapping units are indicated in the map explanation.

The four major categories of surficial (unconsolidated) sediments within the West Branch Delaware River Basin are till, ice-contact stratified drift, outwash, and postglacial alluvium. Till is, by far, the most widespread surficial unit within the basin and is mapped (plate 1) as three distinct units: thin till over bedrock (ground moraine), thick till, and undifferentiated till and colluvium. Ice-contact stratified drift occurs as small, isolated kames, kame terraces, kame moraines, and kame deltas emplaced along the sides of the West Branch Delaware River valley and some of the river's larger tributaries. Outwash and postglacial alluvium form a narrow deposit of coarse gravel and sand that floors the West Branch Delaware River valley and some of its major tributaries. Bedrock is commonly exposed along steep hillsides and ridgetops. The origin and distribution of these major units are discussed below.

Till

Till, the predominant surficial geologic unit within the West Branch Delaware River Basin, covers approximately 89 percent of the area within the basin. Till occurs within the basin as (1) thin till over bedrock (ground moraine), (2) thick till of varying origins, and (3) undifferentiated till and colluvium, which is till that has moved downslope and has been redeposited. The predominance of till in the uplands of the West Branch Delaware River Basin is the direct result of the mode of deglaciation, the steep topography, and the limited volume of external meltwater that entered the basin during deglaciation. Deglaciation in the West Branch Delaware River Basin progressed as a series of six morphosequences, which resulted in the deposition of large amounts of ice-contact sand and gravel in the valley bottoms, ablation till in tributary valleys, and previously deposited lodgment till in the uplands (Kirkland, 1973; Ozvath, 1985). Conversely, deglaciation in the East Branch Delaware River Basin progressed as "ice-stagnation" retreat, which resulted in large masses of ablation till being deposited along the East Branch Delaware River valley bottom, sides, and tributary valleys. Ozvath (1985) refers to ablation till as "valley diamicton" and ascribes its deposition to the resedimentation of supraglacial and englacial debris during ice melting. Large masses of ablation till in the western Catskill Mountains are commonly associated, and may interfinger with, ice-contact stratified-drift, especially in the smaller tributary valleys. This interfingering is a result of the multiple depositional processes (resedimentation, meltwater runoff, and slope colluviation) that occurred during ice ablation, which resulted in wide variability in till composition (Ozvath, 1985). The ablation till in the western Catskill Mountains has been described as a massive, matrix-supported deposit of sand, silt, and gravel with clasts ranging up to boulder size, and is much less compact than the upland lodgment till (ground moraine).

Deposits of ablation till in the West Branch Delaware River Basin and in much of the western Catskill Mountains form a variety of recognizable landforms, such as drumlin-like hills, morainal loops, ridges, knobs, and lateral embankments (large deposits of ablation till containing some stratified beds that were emplaced along the lower valley walls). Rich (1935) was the first to recognize these ablation till features and ascribed their occurrence to deposition by active ice margins. Later investigators, notably Kirkland (1973) and Ozvath (1985), maintained that these features resulted from the disintegration of stagnant ice within the stream valleys, especially valleys that are oriented perpendicular to the southwestward direction of continental ice flow, or that are extremely sinuous in their course. Ozvath (1985) first used the term “lateral embankments” and suggested that they represented supraglacial and englacial debris that collected in troughs between the ablating ice and the valley wall. Large lateral embankments of ablation till are present in many of the small valleys tributary to the West Branch Delaware River, as well as many other streams in the western Catskill Mountains, and typically fill the original bedrock valley to a level that has caused the present-day stream course to shift considerably from the original bedrock thalweg (Reynolds, 2000; Randall, 2001). A notable example of just such an occurrence is located in the West Branch Delaware River valley, about 1 mi east of Walton. Here a large lateral embankment composed of ablation till and (or) colluvium is emplaced along 1.5 mi of the steep southern valley wall. This material has pushed the course of the West Branch Delaware River northward on the order of 1,000 ft. A single well (D–174) south of the river penetrates 170 ft of till and (or) colluvium, is completed in a confined sand and gravel aquifer, and approximates the location of the bedrock thalweg. Some of these lateral embankments may consist partly or entirely of resedimented till. Rich (1935) first described and mapped “thick drift” deposits of “non-morainic” or ablation till in the Catskill Mountains and noted that the till in the lee (southern) side of spurs on valley walls can be so thick as to block the mouths of tributaries and shift them downvalley. Coates (1966) was the first to use the term “till shadows” for thick deposits of lodgment till that were deposited on the southern, or lee, side of bedrock hills with respect to ice flow and later (1981) showed how these till shadows on the south sides of hills in the Appalachian Plateau had shifted the thalwegs of small upland valleys. Large masses of till, whether as lateral embankments or till shadows, can be hydrologically important, in that they can overlie and confine saturated sand and gravel deposits to form locally confined aquifers. Randall (2001) noted that thick till shadows that locally protrude into valley bottoms in the Catskill Mountains are actually products of upland depositional processes and are not related to the deglaciation of the valleys, but rather to the glaciation of the adjacent uplands. The sand and gravel aquifers that are confined by these masses of till are presumably of small areal extent, and may or may not be hydraulically connected to the valley-fill aquifers that occupy most of the valleys in the Catskill Mountains. An example can be found in the log of well D–990, located in a small upland tributary known as Arbuckle Hollow, a tributary to Bagley Brook, approximately 3.5 mi east of the village of De Lancey. This well penetrates 95 ft of boulder till and then 19 ft of sand and gravel before continuing into the underlying bedrock.

Some of the thickest deposits of till in the West Branch Delaware River Basin are deposits of lodgment till that fill upland bedrock valleys and hollows in the headwaters of upland tributaries (Ozvath, 1985). These deposits are the result of ice movement over the divides that separate the West Branch Delaware River Basin from the Susquehanna River Basin to the northwest and the East Branch Delaware River Basin to the southeast. These thick deposits of till are the product of three glacial processes: (1) the dropout of subglacial debris as glacial ice moved over lee side depressions, (2) the meltout of debris from active ice, and (3) the meltout of debris from stagnant basal ice (Ozvath, 1985). Lodgment till in upland valleys and on south-facing slopes can exceed 60 ft in thickness (Soren, 1963); elsewhere, till is deposited as a veneer of ground moraine, which generally does not exceed 6 ft in thickness. One of the thickest till deposits in the West Branch Delaware River Basin is present at Tunis Lake in the headwaters of the Little Delaware River where two wells penetrate 184 ft (D–423) and 234 ft (D–2171) of boulder till in what appears to be a former glacial meltwater channel (or col) that breaches the divide between the West Branch Delaware River Basin to the north and the East Branch Delaware River Basin to the south. Lodgment till and ground moraine in the West Branch Delaware Basin range in matrix composition from sandy silt to silty loam, with minor amounts of clay and are poorly sorted, with embedded clasts as large as gravel size (Ozvath, 1985).

The upland ground moraine and thick till shadows were probably deposited by and beneath the ice sheet as the ice advanced and consist of numerous pebble- and cobble-sized clasts in a compact matrix of sandy silt to silty loam with minor amounts of clay (Ozvath, 1985, p. 48). Ground moraine is poorly sorted, poorly permeable, and non-water-yielding to drilled wells. The colluvium mapped on plate 1 consists of upland till redeposited by gravity near the base of steep slopes and is similar in texture. The ablation till exposed near land surface on the lower slopes and bottoms of many small valleys was inferred by Ozvath (1985) to have melted out of stagnant ice masses, in part reworked by meltwater, and to have been commonly redeposited by landslides as the remaining underlying ice melted. Although ablation till also consists of abundant clasts in a matrix of loamy silt to silty sand, it is usually coarser grained and less compact than the upland ground moraine. Ablation till commonly contains isolated stringers or lenses as much as 1.5 ft thick that range from sandy silt to sand to fine gravel, and at some locations it grades imperceptibly into very poorly sorted sand and gravel (Ozvath, 1985, p. 60–62). These sand and gravel lenses described by Ozvath would probably increase the small yields of large-diameter shallow, dug wells, but are too thin to perceptibly enhance the yield of drilled wells. Ozvath (1985) reported that 20 to 80 percent of the clasts in the ablation till are rounded, because of fluvial transport, and inferred that they were derived from stream gravels present in these valleys prior to the advance of the ice.

Colluvium

Colluvium is one of the major surficial geologic units in the West Branch Delaware River Basin, covering about 2.7 percent of the basin (plate 1). Colluvium is prevalent along steep upland slopes in the West Branch Delaware River Basin, including steep valley walls that border sections of the West Branch Delaware River valley and its larger tributaries. Ozvath (1985) lists three types of colluvium common to the western Catskill Mountains: (1) remobilized till, (2) talus, and (3) landslides. Remobilized till forms gently sloping, hummocky deposits at the base of steep hillsides and is derived from lodgment till that has moved gradually downslope under the influence of gravity during periglacial conditions. Talus consists of angular, boulder-sized slabs of bedrock that became dislodged from outcrops on steep valley walls or cliffs and accumulated at the base of the slope. Landslides are abrupt downslope movements of large masses of earth material that form convex mounds of colluvium at the base of steep slopes, and leave corresponding concave depressions in the hillside, directly upslope from where the material was removed. Large glacial or postglacial deposits of colluvium can partly block a valley in much the same way that a lateral embankment or till shadow can and thus can alter the course of a modern-day stream. The previously discussed lateral embankment of till and colluvium in the West Branch Delaware River valley just east of Walton is a good example of stream alteration. Colluvium that consists of remobilized till can cover and obscure older sand and gravel or thick till deposits on the valley floor and locally confine groundwater in the underlying aquifer.

Ice-Contact Stratified Drift

Geomorphic features within the West Branch Delaware River Basin that consist of ice-contact stratified drift include kames, kame terraces, kame deltas, and kame moraines. These units (plate 1) were deposited as prominent features of six deglacial morphosequences that mark the steady northeastward progression of the receding ice tongue from Deposit to Stamford, a distance of 59 mi. Ice-contact sand and gravel deposits, together with locally overlying outwash, form the bulk of the stratified-drift aquifer in the West Branch Delaware River valley. Proper classification of ice-contact deposits usually requires suitable field exposures of their internal sedimentary structures in order to differentiate between kame terraces, kame deltas, and kame moraines. Kirkland (1979) and Ozvath (1985) remarked on the lack of field exposures of ice-contact deposits, created by gravel mining or borrow pits, in the West and East Branch Delaware Rivers; this lack of field exposures made it difficult for both investigators to classify some of the features that they had mapped as ice-contact material. Similarly, the NRCS soils data used to create the current surficial geologic map (plate 1) do not identify the geomorphology of parent material for soils derived from ice-contact deposits. Therefore, the unit identified as "kame sand and gravel" on plate 1 cannot be classified further (that is; kame moraine, kame terrace, kame delta) based on the current availability of data. A discussion of the geomorphology of each type, however, is useful to the understanding of the differences in the mode of deposition between them.

Kames

Kames are small, rounded hills up to 60 ft in height and 800 ft in width that occupy the valley floor or lower hillslopes of a valley. Kames consist of englacial or supraglacial debris released by ice melting, then briefly transported by meltwater, and then deposited as poorly sorted gravel or sand. A wide range in grain size, sorting, and roundness is typical and reflects the rapid changes in the rates of meltwater flow and sediment release in the glacial environment (Ozvath, 1985).

Kames can be indicative of areas that are favorable for water-supply development where they are largely saturated or hydraulically connected to saturated ice-contact stratified drift at depth or to adjacent or overlying saturated outwash. Surface exposures of kames, even if mostly unsaturated, can act as recharge areas for saturated ice-contact deposits at depth.

Kame Terraces

Kame terraces are large deposits of fluvially deposited ice-contact sediments that once occupied the area between the bedrock valley wall and the ablating ice tongue within the valley. Kame terraces within the West Branch Delaware River Basin can have surface altitudes as high as 100 ft above the valley floor and can be as much as 1,000 ft wide and up to a 0.5 mi long. Many kame terraces have been partly eroded by postdepositional slumping or floods. Kame-terrace sediments within the West Branch Delaware River Basin range from silt to cobble-sized gravel and are crossbedded locally. Ozvath (1985) identified four common sediment facies within kame terraces in the western Catskill Mountains, all of which indicate deposition in a braided glacial-stream environment. As a product of this fluctuating depositional environment, kame terrace sediments can be characterized by large and abrupt changes in grain size between adjacent beds, crossbedding, truncated beds, and various deformation features, such as faults, folds, slumps, and till inclusions. Kame terraces constitute much of the valley-fill aquifer in the West Branch Delaware River Basin and also provide surface pathways where recharge can migrate downward to reach confined portions of the valley fill aquifer.

Kame Deltas

Kame deltas are terrace-like deposits of stratified sand, gravel, silt, and clay that were deposited by meltwater into a proglacial lake. Ozvath (1985) recognized two forms of kame deltas in the western Catskill Mountains—those that flank a valley wall (terraces), and those that extend across the valley. Kame deltas emplaced as flanking terraces were deposited in lakes that developed between the valley wall and the ablating ice tongue, whereas cross-valley kame deltas were deposited in proglacial lakes that developed between the toe of the ice tongue and older downvalley deposits. Kame deltas, whose nearly flat upper surfaces were graded to a former lake level, typically consist of three units of sedimentation: topset beds, foreset beds, and bottomset beds. Topset beds consist of coarse sediment deposited at or above lake level in the channels of meltwater streams. They overlie steeply inclined foreset beds, which consist of sediment deposited at the leading edge of a delta as it advances into a proglacial lake. The foreset beds overlap bottomset beds, which are fine-grained sediments deposited on the floor of the proglacial lake. Foreset and topset beds of kame deltas can contain considerable amounts of coarse sand and gravel, but their altitudes are typically above the modern stream grade and, therefore, are largely unsaturated and generally do not support large groundwater development. Kame deltas may, however, represent potential groundwater recharge areas for saturated ice-contact deposits at depth. Kame deltas are recognized in only a few short reaches of the West Branch Delaware River valley where small glacial lakes were impounded by downstream dams composed of detached blocks of glacial ice. Ozvath (1985) identified several kame deltas in the vicinity of Delhi and Walton—two are located on either side of the sharp "S" bend in the river, southwest of Walton, and two more flank the sharp southward bend in the river just westward of the confluence with the Little Delaware River near Delhi. The logs of several wells in both of these locations show substantial thicknesses of fine-grained lake-bottom sediments, which appear to confirm the existence of two small glacial lakes.

Kame Moraines

Kame moraines are ice-contact landforms that are closely associated with a temporary pause in the retreat of the ice front within a valley; they also are known as outwash heads. Kame moraines generally consist of extremely coarse-grained (to boulder size), poorly sorted gravel that was deposited by fast-moving meltwater streams close to the ice. These deposits generally show deformation features from ice shove and can contain till clasts. Kame moraines indicate the location of a former ice-margin position within the valley, and generally grade downvalley into outwash deposits. In the West Branch Delaware River Basin, kame moraines range in height from 50 to 200 ft above the present flood plain and are commonly located near the junctions with tributary valleys. The common occurrences of kame moraines at the junctions with tributary valleys suggest that their locations were controlled by the availability of the extra sediment load produced by the tributary streams (Kirkland, 1979; Ozvath, 1985).Though not as well sorted as kame terraces and kame deltas, kame moraines may have potential for groundwater development, especially midvalley, where they are overlapped by and buried beneath later outwash and alluvium and are mostly saturated. Kirkland (1979) identified multiple sets of kame moraines, each keyed to an individual morphosequence in the West Branch Delaware River Basin; however, some of these were later reclassified by Ozvath (1985) as either kame deltas or kame terraces.

Outwash, Alluvium, and Inwash

Outwash

Outwash consists of well-sorted, coarse-grained sediments deposited by meltwater streams issuing from the ice front. The relatively steep stream gradients within the West Branch Delaware River Basin, combined with variable meltwater flows and an abundance of coarse-grained sediments, resulted in high-energy, braided streams that deposited tens of feet of coarse sand and gravel outwash. This outwash accumulated on the valley floor as the ice receded and formed what is known as a valley train. Floods and meltwater drainage commonly reworked and redistributed the outwash and adjacent ice-contact deposits during late glacial and postglacial time to form a veneer of alluvium over the outwash. Deposits of valley train outwash and alluvium in the West Branch Delaware River valley are generally less than 2,000 ft wide but can be as much as a 0.5 mi wide at major valley confluences. Outwash, particularly where underlain by ice-contact sand and gravel, forms the principal stratified-drift aquifer in the basin. Outwash,or alluvium underlain by outwash,also floors the larger tributaries to the West Branch Delaware River, except in the upper reaches of the tributaries, but these deposits rarely exceed 1,000 ft in width.

The thickness and horizontal continuity of outwash within the West Branch Delaware River Basin are highly variable as a result of the locally varying amounts of meltwater and sediment that were available within the basin. Where outwash is present in tributary valleys, it typically forms only a veneer over older deposits of ablation till and ice-contact stratified drift. Within the West Branch Delaware River valley, the logs of wells that report fine-grained lacustrine sediments beneath the surficial outwash deposit indicate that the combined thickness of alluvium and outwash ranges from 20 to 40 ft thick near Delhi, 20 to 50 ft thick near Walton, and 20 to 65 ft thick at Deposit.

Alluvium

Alluvium consists primarily of postglacial, fluvially deposited sediment ranging in size from silt, to fine to coarse sand, and to fine gravel, generally less than 10 ft in thickness, and is present as overbank deposits on flood plains. Alluvium is derived from reworked and fluvially sorted outwash, ice-contact, and till deposits, and is generally confined to modern flood plains within a valley or deposited as alluvial fans where small tributaries enter major valleys. Alluvium is generally permeable and on valley floors, typically overlies and grades downward into outwash. Because it can be difficult to distinguish alluvium from the underlying outwash in a valley, both

Kirkland (1979) and Ozvath (1985) generally depict outwash and alluvium as one unit. In tributary valleys where ice-contact deposits line the valley wall, these same deposits can be expected to underlie the alluvium toward the center of the valley. Elsewhere in tributary valleys, alluvium generally overlies deposits of ablation till. Areas of alluvium delineated on plate 1 are based on NRCS soil types that are derived from alluvium, and the thickness of the alluvium is usually much less than 10 ft. Alluvial fans, however, are composed of tens of feet of postglacial alluvium and form rounded, fan-shaped deposits where tributary streams enter the larger valleys. Alluvial fans are mapped separately on plate 1 because they can be major sources of additional recharge to the underlying valley-fill aquifer though streambed infiltration losses where the stream crosses the alluvial fan.

Inwash

Inwash deposits are stratified accumulations of sand and gravel deposited into valleys by tributaries of nonglacial origin. Inwash commonly takes the form of an alluvial fan and may have been deposited atop outwash, or against stagnant ice, where it coalesced with a developing kame terrace. Inwash deposits are typically found in upland headwaters, where outwash deposits would not be expected. Scattered deposits of inwash are found in the upper reaches of some of the tributaries to the West Branch Delaware River. Because the soil types that are derived from inwash are much the same as those that are derived from outwash, inwash is not delineated as a separate unit on plate 1 but is labeled as outwash instead.

Bedrock Geology

The bedrock that underlies the West Branch Delaware River Basin not only provides groundwater to bedrock wells but is a major contributor of groundwater flow (base flow) to the West Branch Delaware River and its tributaries.

Stratigraphy

The entire Catskill Mountain region, including the West Branch Delaware River Basin, is underlain by the informally named Catskill Mountain series (Mather, 1840; Chadwick, 1936) of Upper Devonian age; the series is as much as 6,000 ft thick and consists of marine and nonmarine red and gray sandstones, shales, and conglomerates. Bedrock layers throughout the Appalachian Plateau dip gently southward, as shown by the southward progression from older to younger formations in figure 2, but bedrock in Delaware County is also deformed by broad folds whose axes trend east–northeast, so gentle dips to the northwest and southeast are commonly observed (Soren, 1963). The Catskill Mountains were formed from the dissection of a bedrock plateau by streams and glacial erosion. The highest hilltops and ridges, which form the principal drainage divides, are underlain by various beds of siliceous rocks that are highly resistant to erosion, whereas the lower hilltops and ridges are capped by various sandstone units that also are highly resistant. The valleys are developed along the strike of less competent siltstones and shales, gentle anticlines, and fracture zones (Soren, 1963).

Fisher and others (1970) and Rickard (1975) have divided the nonmarine red and gray sandstones and shales of the Catskill Mountain series, or Catskill facies (Rickard, 1975), in the West Branch Delaware River Basin into five major formations—the Honesdale, Slide Mountain, and upper Walton Formation of the West Falls Group, the lower Walton Formation of the Sonyea Group, and the Oneonta Formation of the Genesee Group (Rickard, 1975, plate 3). The stratigraphically higher (and younger) Honesdale and Slide Mountain Formations occupy the ridgetops of the drainage divide between the West Branch Delaware River Basin and the East Branch Delaware River Basin just south of the Cannonsville Reservoir. The upper Walton Formation occupies the southern uplands within the West Branch Delaware River Basin and its ridges also form part of the drainage divide between the West and East Branch Delaware Rivers. The lower Walton Formation underlies the lower slopes and valleys of the main tributaries south of Delhi, whereas the Oneonta Formation underlies the upper West Branch Delaware River and its tributaries from Delhi northeastward to its headwaters just beyond Stamford (Fisher and others, 1970). The areal distribution of these major bedrock formations within the West Branch Delaware River Basin is illustrated in figure 2.

Structure and Folding

The Catskill Mountain series rocks in Delaware County lie in broad, low folds, striking in a northeasterly direction within a larger synclinal structure whose trough axis plunges slightly southwestward and appears to lie wholly within Delaware County (Soren, 1963). The East and West Branch Delaware Rivers lie along low anticlines with a syncline occupying the intervening uplands. Soren (1963) observed anticlinal folds along highway exposures near the Pepacton Reservoir and near the village of Apex, N.Y., in the West Branch Delaware River Basin. Woodward (1957) estimated that the axis of the folding is approximately 75° N to 80° E, and appears to extend across Delaware County. The limbs of the folds dip at low angles, generally less than 5 degrees (°), to the southeast and northwest (Soren, 1963). The steepest dips measured by Soren (1963) were at outcrops at Delhi, in the bed of Steele Brook, where gray shale beds of the lower Walton Formation dip about 12° to the northwest, and along State Highway 10, north of Apex, N.Y., where an anticlinal fold whose limbs dip 8° to the northwest and 5° to the southeast, is exposed. As Soren (1963) points out, folds can affect the occurrence and movement of groundwater. The inclination of beds in the limbs of folds and along the plunge of the folds can produce artesian pressures in more permeable beds of sandstone lying between shale beds of lower permeability. Beds of lower permeability, such as shales, can also serve as barriers to the movement of groundwater between adjacent folds.

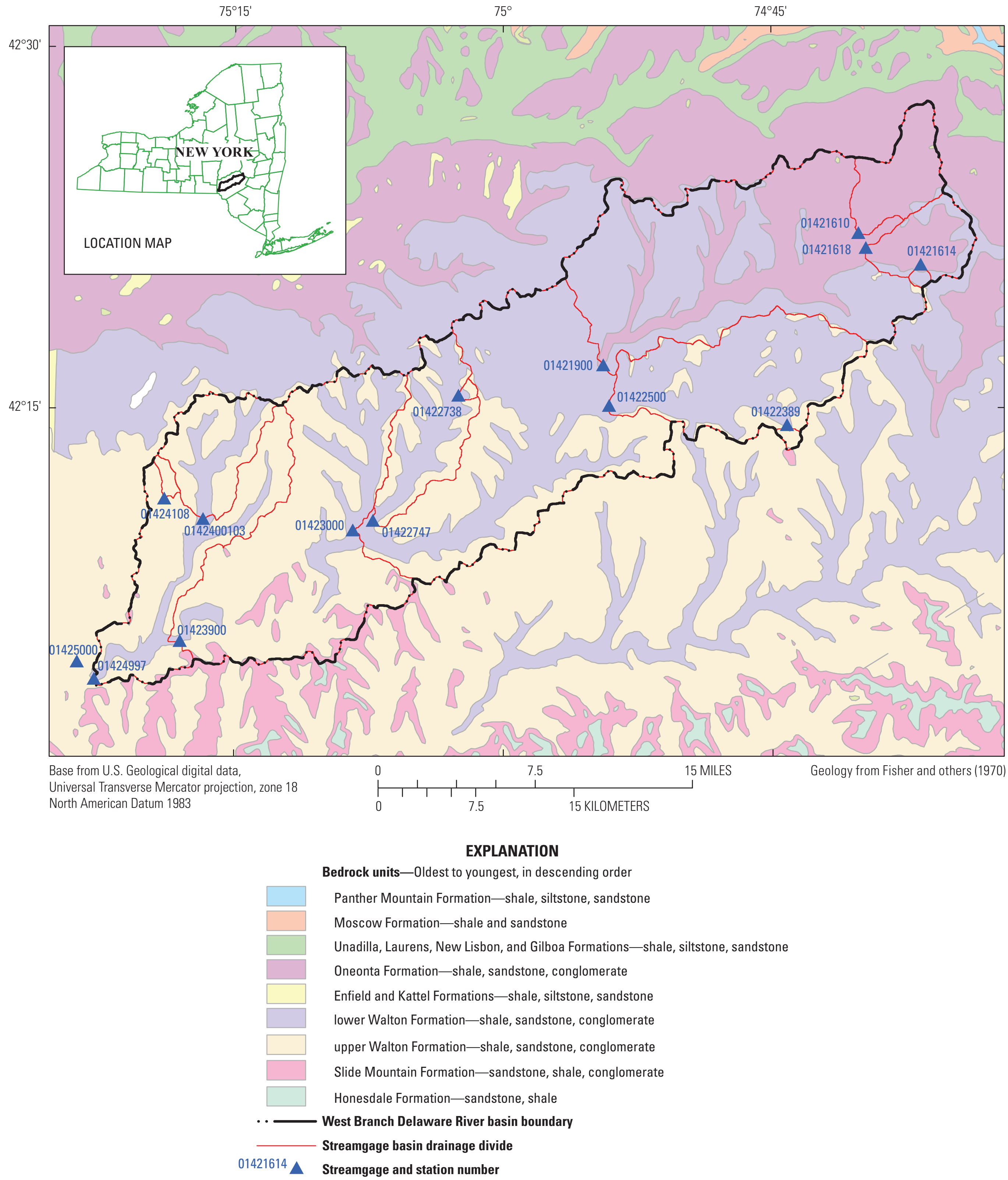

Figure 2. Distribution of major bedrock units within the West Branch Delaware River Basin in southeastern New York. Bedrock units listed in descending order from oldest to youngest.

Faults and Jointing

Little surface evidence of faulting has been reported in the West Branch Delaware River Basin and in Delaware County in general, because of a lack of marker beds and a scarcity of accessible rock outcrops (Soren, 1963). Soren (1963) observed a thrust fault with a displacement of several feet in the anticlinal fold seen north of Apex. This fault displayed a dip of about 15° to the northeast. Soren (1963) also noted that the bedrock in Catskill Mountain series rocks in Delaware County is strongly jointed (fractured), with sets of closely spaced joints observed in shales, and joints with spacings of several feet in the thicker sandstones. Two vertical joint sets strike northeast and northwest, respectively, with the planes of the joint sets nearly perpendicular to the bedding plane in the rock. A third joint set, which is parallel to the bedding plane, intersects the two vertical joints sets, and all three appear in most of the beds of Catskill Mountain series rocks. The two vertical joint sets are roughly perpendicular—one striking northeast, from 15° N to 35° E, and the other striking northwest, from 25° N to 80° W (N.M. Perlmutter and E.H. Salvas, U.S. Geological Survey, written commun., 1957). These roughly orthogonal vertical fracture sets facilitated the quarrying of bedrock from hillsides by glacial ice to produce horizontal surfaces and ledges bounded by nearly vertical cliffs, commonly tens of feet high (Soren, 1963; Parker and others, 1964). The joint sets also serve to increase the permeability of the rock and are the reason for the relatively high yields of bedrock wells in this region. Bedding plane openings, or joints, are important contributors to the secondary porosity of the bedrock, as are the vertical joints and fractures that intersect these bedding plane openings. The continuity and connectivity of these features and their ability to transmit water (transmissivity) are important factors in determining the larger scale transmissivity and storage capacity of the bedrock aquifer. The sandstones and shales of the Catskill Mountain series rocks in the West Branch Delaware River Basin show typical sedimentary rock structure and range from thin shale layers up to ⅜-inch (in.) thick, to individual beds of sandstone more than 4 in. thick (Soren, 1963). The beds of the Catskill Mountain series have been characterized as poor to moderately good aquifers whose well yields can vary widely within hundreds of feet (Parker and others, 1964). In general, the sandstone beds are much more permeable than are the shale beds, although some massive sandstone units are so completely cemented and lacking in fractures that they transmit little water (Parker and others, 1964).

Stress Relief Fracturing

Stress relief in valleys has been shown to be the principal factor in enhancing the secondary permeability of clastic sedimentary rocks (Wyrick and Borchers, 1981). Stress relief refers to the fracturing, arching, and faulting of sedimentary rocks beneath a bedrock valley floor and along the valley walls in response to the removal of rock by erosional processes. The removal of rock to produce a bedrock valley creates tensional forces along the valley walls and resultant upward forces on the bedrock that directly underlies the valley floor (fig. 3). These forces typically produce vertical tensile fractures in bedrock on the valley walls and vertical fracturing, low-angle faulting, and arching of beds beneath the valley floor. The tensile fractures on the valley walls can result in blocky or steep cliffs with nearly vertical faces, especially in structurally competent rocks such as massive sandstones, whereas the vertical and horizontal compressional forces on the rock underlying the valley floor typically produce arching of beds and associated vertical fracturing. There is ample evidence of stress relief fracturing in the valleys of the Catskill Mountain region. Soren (1963) reported anticlinal crests (folds) in the East and West Branch Delaware Rivers near the Pepacton Reservoir and near Apex. Heisig (1999) depicted stratigraphy (based on natural gamma radiation logs) in the Batavia Kill valley near Windham, N.Y., east of the West Branch Delaware River Basin that appears to show arching of beds (or an anticlinal structure) beneath the thalweg of the bedrock valley there. According to Woodward (1957), the East and West Branch Delaware Rivers lie along anticlinal folds whose orientation (75° N to 80° E) nearly matches the orientation of the valleys. On the basis of this evidence, it can be reasonably assumed that vertical fracturing is present in bedrock beneath the West Branch Delaware River valley and many of its larger tributaries. Valley-bottom and valley-side fracturing caused by stress relief improves the secondary permeability of rock to the extent that yields from bedrock wells in these areas are typically higher than those of wells drilled into the upper hillsides or hilltops. The general features of stress relief fracturing are illustrated in figure 3.

Well Yields

Records of 199 wells drilled into the Catskill Mountain series within Delaware County indicate well depths ranging from 18 to 687 ft, with a median depth of 158 ft (Soren, 1963); most well depths range from 100 to 300 ft. Yields range from 0 to 450 gallons per minute (gal/min), with a median yield of about 15 gal/min. Specific capacities range from less than 0.2 to 4 gal/min per foot [(gal/min)/ft] of drawdown (N.M. Perlmutter and E.H. Salvas, U.S. Geological Survey, written commun., 1957). The maximum known yield from a bedrock well in the West Branch Delaware River Basin (400 gal/min) is from well D–420, a 10-in.-diameter well that is 172 ft deep and is completed in the lower Walton Formation, which underlies most of the West Branch Delaware River valley. Similarly, the maximum known yield (550 gal/min) from a bedrock well within Delaware County is from well D–15, a 12-in.-diameter industrial well completed in sandstone and shale near Sidney, N.Y. (within the Susquehanna River Basin). Eight bedrock wells (D–33, D–88, D–90, D–91, D–102, D–103, D–353, and D–420) in the West Branch Delaware River Basin have yields that exceed 100 gal/min. These high-yielding bedrock wells are all situated on the valley floor where overlying sand and

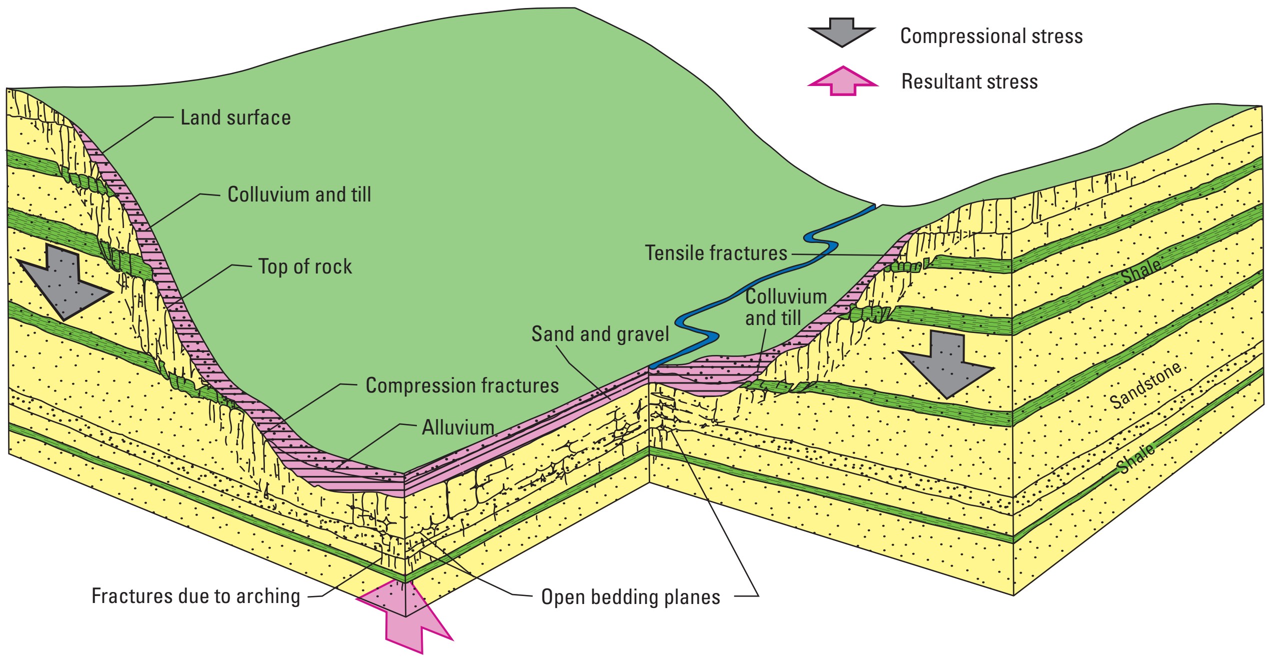

Figure 3. Generalized geologic section showing features of stress-relief fracturing. From Wyrick and Borchers (1981, fig. 3.2–2).

gravel deposits likely enhance the well yields. Wells that are completed in the Catskill Mountain series and are situated on valley floors commonly exhibit artesian flow because potentiometric heads in the underlying bedrock are typically above land surface in these locations. Data from exploratory borings made in the 1930s and 1940s along the routes of the nearby East and West Delaware Aqueducts indicate artesian flow at several borings in valley floor and lower hillside settings with a potentiometric surface more than 10 ft above land surface (Reynolds, 2000).

Saline Groundwater

Groundwater from the Catskill Mountain series generally is of excellent quality and is typically used for domestic, industrial, and municipal supplies without treatment (Parker and others, 1964). Hardness ranges from very soft to moderately hard, and dissolved solids concentrations are generally low. Iron concentrations are typically low (0.01–0.17 milligram per liter [mg/L]), but can be elevated locally (Parker and others, 1964).

Despite the documented high quality of groundwater from the Catskill Mountain series, saline groundwater has been reported at depth within the West Branch Delaware River Basin and within the Schoharie Creek Basin to the east. Soren (1963) reported two bedrock wells, both located on the floor of the West Branch Delaware River valley, which produced water with elevated chloride concentrations. Water from a bedrock well at Deposit (D–114), which is 208 ft deep, yielded water with a chloride concentration of 310 mg/L when first drilled in 1946. Also in 1946, well D–102 at Walton (420 ft deep) initially had a chloride concentration of 800 mg/L, but had a chloride concentration of only 126 mg/L when it was resampled in 1957. Many of the deep bedrock wells drilled into the Catskill Mountain series rocks also produce naturally occurring methane gas, in addition to producing saline water. Well D–32, a 505-ft-deep bedrock well on the valley floor just southwest of Delhi, produced flammable gas (methane) and hydrogen sulfide gas when drilled in 1941, reportedly produced a gas flame 3 to 5 ft high for more than a year after being abandoned, and was finally cemented shut in 1947 (N.M. Perlmutter and E.H. Salvas, U.S. Geological Survey, written commun., 1957). Newland and Hartnagle (1932) reported that a brine spring existed in the Elk Creek valley, about 4 mi north of Delhi as early as 1833. A subsequent boring to 394 ft at this location produced enough brine for the commercial manufacture of salt, and small amounts of natural gas were observed in the water. In 1864, an exploratory well was drilled near the site of the original spring (MacDonald test hole; plate 1) to a depth of 750 ft. Insufficient natural gas was found for the well to be economically developed, and the well was abandoned. In 1924, however, the gas pressure on the well was tested at 25 pounds per square inch, and Newland and Hartnagle (1932) estimated that the well could produce enough gas to supply a single home for several years. N.M. Perlmutter and E.H. Salvas (U.S. Geological Survey, written commun., 1957) also reported a 462-ft-deep bedrock well in central Sullivan County, N.Y., that produced natural gas (methane) and saline water from a gray shale unit. All these wells probably intersect marine shales of the Catskill Mountain series and tap naturally occurring brine (connate water). Saline groundwater has also been reported in deep wells completed in Catskill Mountain series rocks within the adjacent Schoharie Creek Basin to the east. Heisig (1999) reported three bedrock wells within the Batavia Kill valley near Windham that produce very saline groundwater from depths ranging from 420 to 489 ft. Several bedrock wells within the Batavia Kill valley were geophysically logged in that study and water samples were obtained at selected intervals within the boreholes with a down-hole point sampler. Dissolved chloride concentrations in groundwater entering the boreholes from fractures ranged from 370 to 13,000 mg/L (Heisig, 1999, app. B). However, not all deep bedrock wells that intercept saline water at depth produce nonpotable water because considerable mixing generally occurs within the borehole. Moreover, the location of the well with respect to the valley will affect the flow within the borehole. Wells that are located high on the valley walls or on hilltops are generally in areas of groundwater recharge where the vertical gradient, and thus the flow within the well bore, are downward. Conversely, wells on the valley floor are in areas of groundwater discharge where the vertical gradient, and thus the flow within the well bore, are upward. Bedrock wells located on valley floors and that intercept saline groundwater at depth, therefore, usually yield water that gradually becomes nonpotable through the upward movement of saline water within the well bore. In a study of wells that penetrated either saline water or gas in the Upper Devonian bedrock of Chemung, Tioga, and Broome Counties, N.Y., Williams (2010) found that the base of freshwater circulation (that is, the top of saline water) appeared to be about 800 ft below land surface in upland settings, but only 200 ft below land surface on the valley floors. At depths greater than 200 ft below the valley floors groundwater in the Upper Devonian bedrock, and in some places in the immediate overlying glacial drift, was saline. The frequency of occurrence of methane gas increased with depth in the bedrock, with some pockets of gas present above the base of the freshwater circulation (Williams, 2010). The two bedrock wells (D–102 at Walton and D–114 at Deposit) that have penetrated saline water in the West Branch Delaware River Basin appear to show a similar depth of freshwater circulation below the valley floor.

Groundwater Flow System

The sequence of permeable sandstone units alternating with less permeable shale units within the Catskill Mountain series forms a series of stacked aquifers separated by confining units of varying thickness, but generally thinner than the aquifer units. Weathering, glacial loading and unloading, and stress relief through the erosion of bedrock in the valleys have made exposed rock and rock nearest to the mountainsides typically more jointed and fractured than the unexposed rock deep within each mountain or ridge. This enhanced jointing increases the secondary permeability in these areas and allows groundwater in the highly jointed sandstone to flow readily to points of discharge (springs) along the hillside, just above confining shale beds, as illustrated in figure 4. A small unsaturated zone develops in the upper part of each sandstone unit near the hillside, although the entire rock section within the core of the mountain is saturated. Thus, the mountainsides commonly exhibit a stepwise pattern of steep sandstone faces with springs at their bases, separated by gentler slopes of shale. Horizontal joints and permeable bedding-plane fractures typically form at the contact between lithologically dissimilar rock units; therefore, groundwater within a saturated sandstone unit typically discharges at the contact with the underlying shale unit as a contact spring. These springs can be ephemeral features that flow during only the wet spring season (March and April), but may flow continuously if the saturated zone above the springs is thick enough. These sandstone units also are saturated but less fractured or jointed where they extend into the core of the mountain, and groundwater within these units moves mainly as slow, diffuse flow through small intergranular spaces and small, discontinuous fractures and, therefore, probably contributes little to contact springs.

Groundwater within saturated sandstone in valley segments that contain thick deposits of ablation till occurs generally under confined conditions, with groundwater levels typically rising to above land surface in bedrock wells on or near the valley floor. For example, records of two test holes drilled into sandstone and basal till along the route of the East Delaware Aqueduct crossing of Beaver Kill at Lewbeach in adjacent Sullivan County indicate that artesian flow from a 3-in.-diameter casing was as much as 18 gal/min, and heads ranged from 12 to 13 ft above the valley floor (Reynolds, 2000). The large head difference between the water table in the valley and the potentiometric surface of the confined, fractured sandstone at depth may indicate low vertical hydraulic conductivity within the bedrock or within a till confining unit between the bedrock and the outwash and may explain the relatively high base flows of streams in this region.

Springs

Springs are a source of domestic groundwater supplies for much of the rural population of the West Branch Delaware River Basin, and much of the Catskill Mountain region. Well and spring inventories were conducted by the USGS during previous groundwater investigations of Delaware County (Soren, 1963) and the Delaware River Basin in New York (N.M. Perlmutter and E.H. Salvas, U.S. Geological Survey, written commun., 1957). Perlmutter and Salvas inventoried about 300 springs that discharge from the Catskill Mountain series rocks in the Appalachian Plateau, which includes both the West and East Branch Delaware River Basins and most of adjoining Sullivan County. Nearly all these springs were situated on hillsides, originated from bedding-plane openings or other fractures, and discharged only 2 to 3 gal/min, although a few exhibited discharge rates as high as 106 gal/min (N.M. Perlmutter and E.H. Salvas, U.S. Geological Survey, written commun., 1957, p. 21). Soren (1963) published records of 184 representative springs in Delaware County, nearly all of which

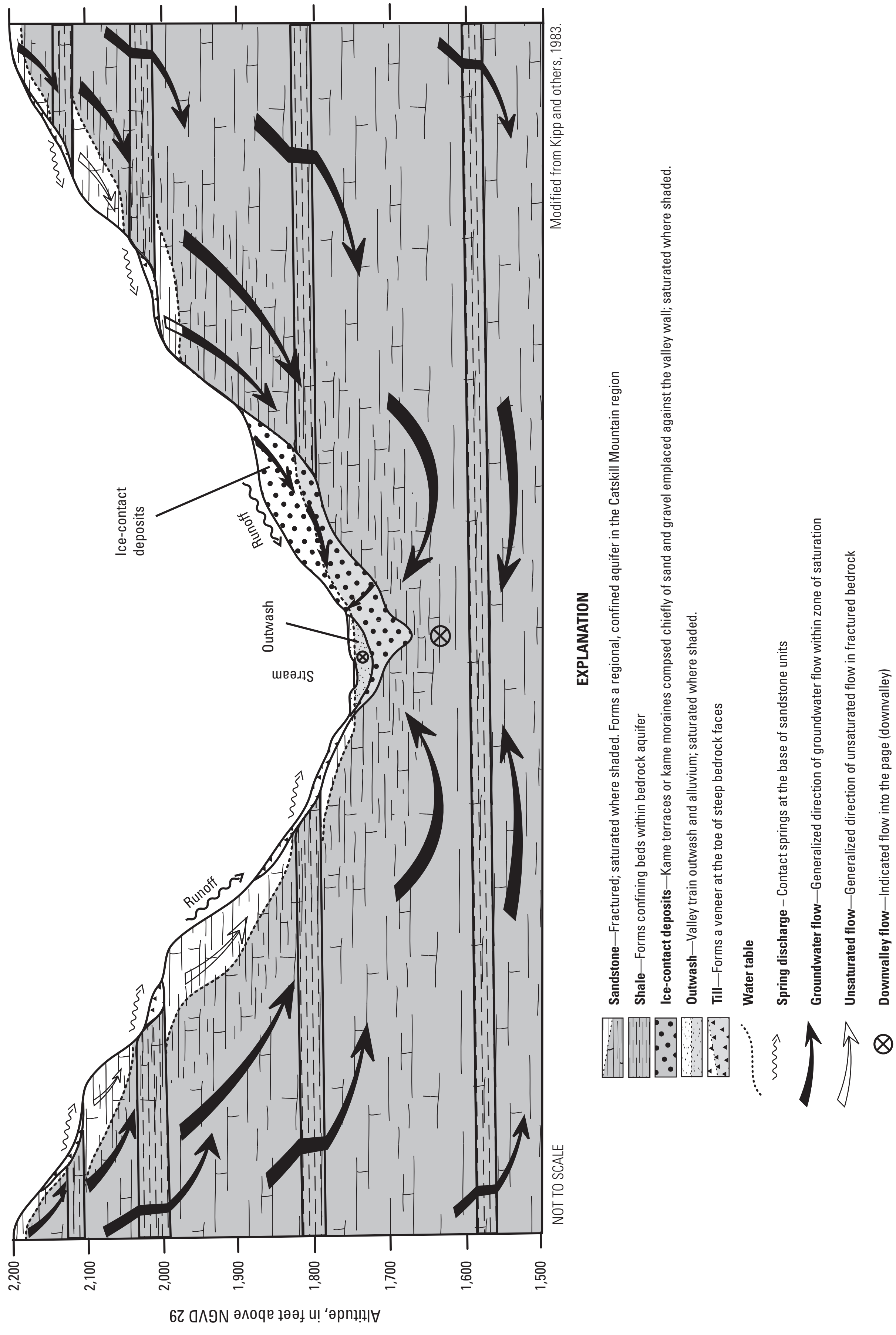

Figure 4. Conceptual diagram of groundwater flow within bedrock and stratified-drift aquifers within the West Branch Delaware River Basin in southeastern New York. From Reynolds (2000, fig. 8).

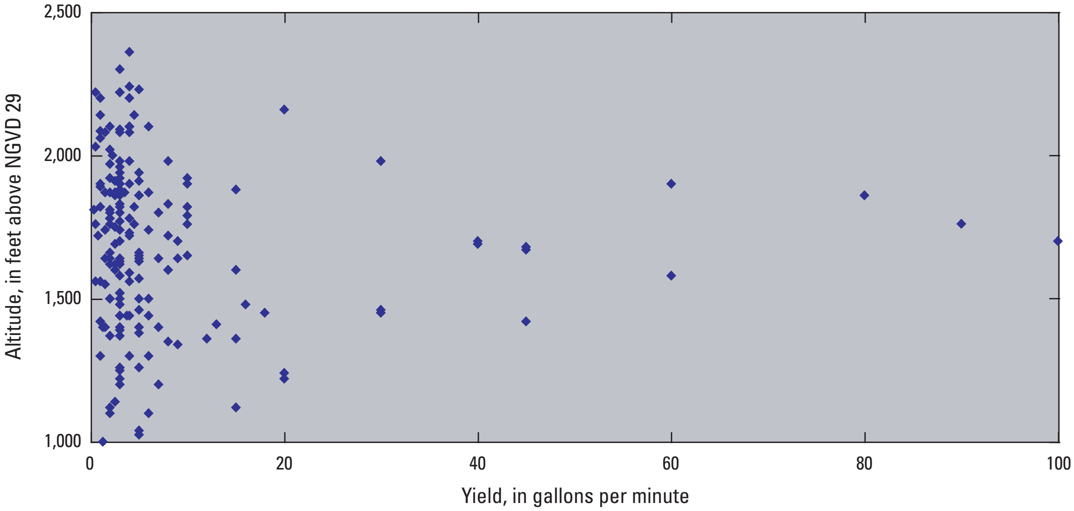

Figure 5. Yield of 178 springs in Delaware County, New York, as a function of altitude. Data are from Soren (1963). NGVD 29, North American Vertical Datum of 1929.

discharged from Catskill Mountain series sandstones. Most of these springs were used as domestic supplies for homes and farms, although some were used for public water supplies for several villages. Yields of 178 of these springs were measured by the USGS from October 1948 through February 1949; the highest yield (100 gal/min) was from a group of three springs that supply the village of Downsville, N.Y., in the East Branch Delaware River Basin. The average yield for these 178 springs, which include 11 public-water supplies, was 8.5 gal/min, with a median yield of 3 gal/min, although most of the domestic springs had yields of less than 5 gal/min. Records of these 178 springs show that they range in altitude from 1,000 ft to 2,360 ft above the National Geodetic Vertical Datum of 1929 (NGVD 29), with a mean altitude of 1,676 ft. A plot of yield as a function of altitude for these 178 springs (fig. 5) indicates that most of the yields were less than 10 gal/min and that most of the springs are at altitudes ranging between 1,400 and 2,000 ft above NGVD 29.

Many small villages within the West Branch Delaware River Basin still rely on springs as their primary source of water, but often use wells as an auxiliary supply. Soren (1963) reported that, in 1960, more than half of the small municipalities (17 out of 31) within Delaware County relied on springs to supply all or part of their drinking water, and water-use data for 2000 (New York State Department of Health, written commun., 2000) indicated that there were 15 small municipalities in Delaware County that continue to obtain all or part of their water needs from springs. Several small villages in the West Branch Delaware River Basin still use springs for all or part of their municipal supply. For example, De Lancey relies on three springs, with an average yield of 10 gal/min, to serve a population of 135. Similarly, the Hamden Water District relies on four springs to serve a population of 150 people, and the village of Bloomville, N.Y., relies on a combination of springs and wells to supply a population of 300 (Soren, 1963; New York State Health Department, 1982). All these municipal-supply springs issue from fractured Catskill Mountain series sandstones. The prolific use of springs for domestic and municipal water supplies in the Catskill Mountain region appears to indicate a lesser dependence on drilled wells for drinking water than in other parts of New York. The abundance of springs issuing from Catskill Mountain series sandstones reflects the relatively high secondary permeability of these rocks because of the presence of both vertical and bedding-plane fracture sets and the effect of stress-relief fracturing on the valley walls. The abundance of springs has a pronounced effect on the base flow of tributary streams within the West Branch Delaware River Basin, as many of the small tributaries originate as spring discharge from hillsides (N.M. Perlmutter and E.H. Salvas, U.S. Geological Survey, written commun., 1957).

Marcellus Shale

The Marcellus Shale, a black, organic-rich, gas-bearing shale that forms the basal member of the Middle Devonian Hamilton Group in New York, is one of several black shales that occupy the Appalachian Plateau. The Marcellus Shale extends from northeastern Kentucky into West Virginia, northeastward through Pennsylvania and northwest Maryland, and into the Southern Tier of New York, as well as Delaware and Sullivan Counties in New York. The Marcellus Shale is the most widespread Devonian gas-bearing shale sequence in New York and consists of black "sooty" shale with some interbedded gray shales and dark gray to black limestones (DeWitt and others, 1993). The Marcellus Shale reaches a thickness of about 1,000 ft in central Pennsylvania and thins to the north, west, and south (DeWitt and others, 1993). However, the net thickness of organic-rich black shales within the Marcellus is considerably less—approximately 250 ft in eastern Bradford County, Pa., and Tioga County, N.Y., and only about 150 ft thick in Delaware County (Milici and Swezey, 2006). The Marcellus Shale has been further subdivided into two gas-bearing black shale units—the Oatka Creek Shale Member and the lowermost Union Springs Member—both of which are

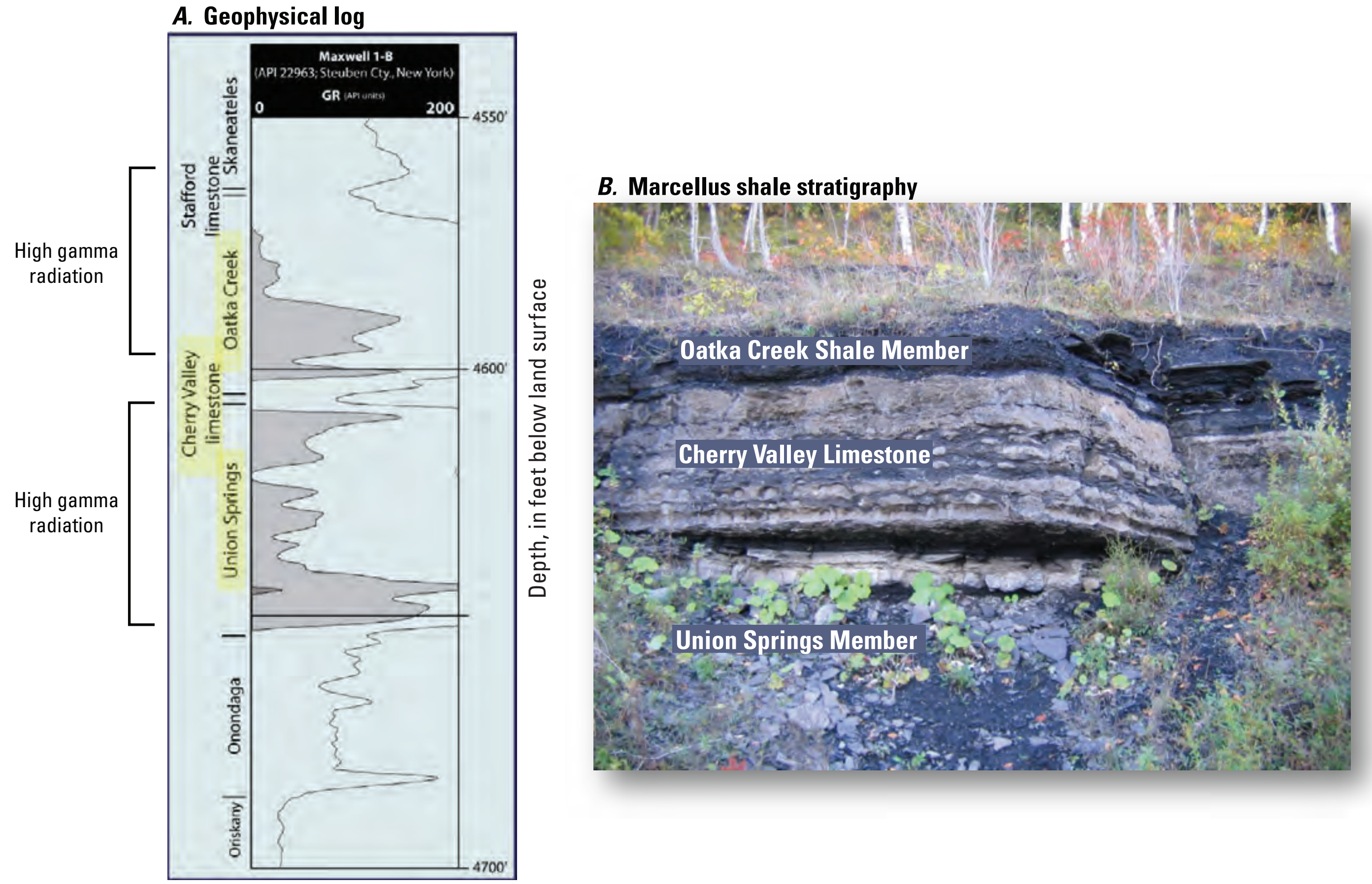

Figure 6. *A*, Geophysical log showing typical gamma log response and *B*, photograph showing typical stratigraphy of the Marcellus Shale in New York. The shaded portion of the gamma response curve represents an upward shift in scale to 200 to 400 American Petroleum Institute (API)units and indicates the high gamma radiation response characteristic of black shales. Geophysical log modified from Lash and Engelder (2009); photograph by J.H. Williams, U.S. Geological Survey.

separated by the intervening Cherry Valley Limestone Member (fig 6). The base of the Marcellus Shale conformably overlies the Onondaga Limestone (Rickard, 1975).

New developments in horizontal drilling and hydraulic fracturing have made the Marcellus Shale the newest exploitable source of natural gas in the Northeastern United States. There is, however, concern among State regulatory agencies and the general public in New York and Pennsylvania about the possible contamination of stratified-drift and bedrock aquifers from proposed gas well drilling operations. Along with the natural gas, the wells would produce highly mineralized brine from the Marcellus Shale, large volumes of drilling fluids with numerous additives, and drill cuttings. The chemical and radiologic qualities of these fluids and solids have not been well documented, but will have to be dealt with at the drill site and during transportation and disposal (Soder and Kappel, 2009). Therefore, State, county, and municipal, governmental agencies are seeking information that will help them discern if these drilling operations may contaminate overlying aquifers that supply potable water.

Ten deep exploratory test holes that encircle the West Branch Delaware River Basin give information on both the thickness and depth to the Marcellus Shale (table 1). The thickness of the Marcellus Shale (Marcellus Formation of the Hamilton Group; Rickard, 1975) ranges from about 600 to 650 ft along the northern watershed divide with the adjacent Susquehanna River Basin (test holes Fowler Finch 1, Hazlett Merrit 1, and Hirsch K1) to about 750 ft along the southern divide with the East Branch Delaware River Basin (test holes Holdridge Charles 1, Lanzilotta 1, and Weickert F1) and thins slightly to about 660 ft further westward (test hole Campbell). The depth to the top of the Marcellus Shale ranges from about 2,600 to 2,900 ft in the Ouleout Creek and Treadwell Creek valleys to the north (test holes Leslie Caroline E1 and Hazlett Merrit 1) to 3,240 ft in the uplands near the northern watershed divide (test hole Hirsch K1). Similarly, the depth to the top of the Marcellus Shale along the southern divide with the East Branch Delaware River Basin ranges from about 3,500 to 4,150 ft in three upland test holes (Holdridge Charles 1, Lanzilotta 1, and Weickert F1). The greatest depth to the Marcellus Shale of about 4,390 ft is seen at the Campbell HA test hole southeast of De Lancey in the uplands of the East Branch Delaware River Basin. Two test holes (Grant 6 and Grant C1a) in the Ouleout Creek valley to the north indicate that the thickness of the Union Springs Member of the Marcellus Shale is about 28 ft thick in this location.

Stratified-Drift Aquifers

The location and thickness of stratified-drift aquifers in the West Branch Delaware River Basin are directly related to the distribution of outwash and ice-contact deposits. In general, the upper and middle reaches of the West Branch Delaware River contain thick sections of outwash and sand and gravel, with thick beds of fine-grained lacustrine sediments appearing in only the lowermost valley reach. The unconsolidated sediments in the small tributary valleys become less stratified and sorted as the valley size decreases and generally include large thicknesses of till, and what little stratified drift is present consists of poorly sorted ice-contact material (Ozvath and Coates, 1986). The main valley of the upper West Branch Delaware River (Stamford to Delhi) and middle West Branch Delaware River (Delhi to Walton), however, contains large amounts of ice-contact sand and gravel and outwash that together form productive sand and gravel aquifers that are generally under water-table (unconfined) conditions. The lowermost reach of the West Branch Delaware River (Walton to Deposit) contains an additional thin, basal sand and gravel aquifer confined beneath thick sequences of lacustrine clay, silt, and fine sand. The distribution, thickness, and composition of the stratified-drift aquifers in each of these valley segments are discussed below.

Upper West Branch Delaware River

The upper West Branch Delaware River, the 20-mi reach from the river's headwaters near Stamford to the confluence with the Little Delaware River at Delhi (pl. 1), is characterized by long stretches of valley filled with ice-contact features such as kame terraces and kame moraines, bisected by a narrow ribbon of valley-train outwash. The valley fill in this section consists mostly of ice-contact sand and gravel, overlying a basal till, all of which is overlain by valley-train outwash. The valley floor in this stretch, as throughout most of the West Branch Delaware River valley, averages about 2,500 ft in width. The thickness of the valley fill, which includes fine- and coarse-grained sediments, ranges from 130 ft at Hobart (well D–51, a supply well for the Hobart Water Company) to 119 ft at Bloomville (well D–503), and to 142 ft at East Delhi (well D–2208). Each of these three wells is located where a major upland tributary valley joins the West Branch Delaware River valley; the limited well data suggest that depth to bedrock is greatest near such junctions. For example, near Delhi where

Table 1. Thickness of and depth to the Marcellus Shale in selected deep test holes in Delaware County, New York.

[Data are from New York State Museum Empire State Oil and Gas Information System (ESOGIS) database, 2010, http://esogis.nysm.nysed.gov/esogis/index.cfm. Horizontal datum is North American Datum of 1983 (NAD 83). The bottom of the Marcellus Shale is the Cherry Valley Limestone Member of the Marcellus Shale (Rickard, 1975). NGVD 29, North American Vertical Datum of 1929; NA, not applicable]

Well name	Latitude	Longitude	Hole depth, in feet	Depth to Marcellus Shale top, in feet	Depth to Marcellus Shale bottom, in feet	Marcellus thickness, in feet	Land surface altitude, in feet above NGVD 29	Marcellus Shale top altitude, in feet above NGVD 29	Marcellus Shale bottom altitude, in feet above NGVD 29
Lanzilotta 1	42.27354	-74.62734	9,075	3,560	4,305	745	1,835	-1,725	-2,470
Fowler Finch 1	42.31691	-75.23368	7,973	3,376	3,973	597	1,658	-1,718	-2,313
Campbell HA	42.18284	-74.92141	10,992	4,393	5,055	662	1,776	-2,617	-3,279
Hirsch K1	42.37398	-75.04223	5,327	3,240	3,884	644	1,990	-1,250	-1,894
MacDonald	42.33135	-74.87257	750	NA	NA	NA	1,570	NA	NA
Hazlett Merrit 1	42.34249	-75.0814	4,570	2,920	3,575	655	1,457	-1,463	-2,118
Weickert F1	42.29766	-74.62458	6,740	3,512	4,250	738	1,999	-1,513	-2,251
Holdridge Charles 1	42.18614	-74.68299	6,681	4,151	4,905	754	1,704	-2,447	-3,201
Leslie Caroline E1	42.39048	-75.04415	7,952	2,625	3,260	635	1,485	-1,140	-1,775
Grant 6	42.39777	-75.05277	5,600	3,348	3,375	[1]27	1,595	-1,753	-1,780
Grant C1a	42.39906	-75.05232	5,580	3,393	3,421	[1]28	1,635	-1,758	-1,786

[1]Thickness of the Union Springs black shale unit overlying the Onondaga Limestone.

only small tributaries enter, the floor of the West Branch Delaware River valley narrows to about 1,000 feet, and several wells document a range in aquifer thickness from 42 (well D–861) to 72 ft (well D–984).

Communities within this reach that obtain municipal water from wells that are screened in the valley-fill aquifer include Delhi and Hobart. Two supply wells in Delhi (D–256 and D–286) are 50 ft deep, are screened in ice-contact sand and gravel, and yield 500 gal/min. Hobart has a 130-ft-deep well screened in ice-contact sand and gravel that yields 100 gal/min.

Although most of the valley in the Stamford-Delhi reach of the river is filled with ice-contact sand and gravel and outwash, limited amounts of fine-grained lacustrine sediment, deposited in short-lived proglacial lakes, exist within the valley fill. For example, the log of well D–1442 at East Delhi, near the confluence of Elk Creek, shows 40 ft of alluvium and outwash, overlying a 60-ft section of silt, which in turn overlies at least 13 ft of confined ice-contact sand and gravel. Depth to bedrock in this area is approximately 140 ft. The log of nearby well D–2208 similarly shows 20 ft of alluvium and outwash, overlying 117 ft of silt and clay, which in turn overlies 5 ft of ice-contact sand and gravel atop bedrock. This well produces 45 gal/min from this thin confined aquifer.

Middle West Branch Delaware River

The middle West Branch Delaware River, the 16-mi reach from Delhi southwest to Walton (pl. 1), is also characterized by large kame terraces and kame moraines along both valley walls, with narrow valley-train outwash and alluvium in the center. As in the upper reach, the valley fill consists mostly of ice-contact sand and gravel that overlies a discontinuous basal till, all of which is overlain by valley-train outwash. The valley width ranges from about 3,000 ft at the confluence of the Little Delaware River just south of Delhi to about 4,500 ft at De Lancey at the confluence of Bagley Brook to almost 5,200 ft at Walton where West Brook and East Brook converge with the West Branch Delaware River. Some of the thickest outwash deposits in the West Branch Delaware River valley are located in these areas where tributary valleys provided pathways for sediment-laden glacial meltwater to contribute large volumes of outwash. In contrast, the valley width decreases to less than 1,000 ft just east of Walton where a large deposit of colluvium at the base of the south valley wall has buried the main bedrock channel and moved the course of the river northward. This mass of colluvium is identified in the log of well D–174, which penetrates 170 ft of till (interpreted as remobilized till and colluvium) and is completed in a thin, confined sand and gravel layer. The thickness of the valley-fill aquifer ranges from about 70 ft just south of Delhi (wells D–420 and D–421) to between 90 ft (well D–88) and 110 ft (well D–1604) near De Lancey to more than 140 ft (wells D–1393 and D–506) near the hamlet of Hawleys, N.Y. The 6-mi valley reach from Hawleys west to Walton is flanked with large kame terraces on both valley walls, and the aquifer thickness ranges from 80 to 90 ft (wells D–173 and D–848) and composes almost entirely ice-contact sand and gravel. The aquifer thins to less than 20 ft where the valley width narrows to less than 1,000 ft about 1 mi east of Walton because of a large mass of colluvium that has diverted the course of the river northward and filled the bedrock thalweg with more than 170 ft of material (well D–174). Well yields from the valley-fill aquifer range up to 500 gal/min for two 12-in.-diameter supply wells (D–256 and D–286) for Delhi that are screened in ice-contact sand and gravel. Other municipalities that rely on groundwater from the valley-fill aquifer are Hamden (well D–254) and Walton (wells D–253 and D–493). Numerous commercial dairy-processing facilities in the valley also require large well yields, as exemplified by a 65-ft-deep, 510-gal/min supply well (D–261) at Walton.

Just south of Delhi, the Little Delaware River enters the main West Branch Delaware River valley. Limited well data in the Little Delaware River valley indicate that the valley fill consists mostly of till and isolated ice-contact deposits with an overlying veneer of alluvium, and ranges in thickness from 80 (well D–1914) to 27 ft (well D–754). One of the thickest till deposits in the entire West Branch Delaware River Basin, however, occurs in the headwaters of the Little Delaware River at Tunis Lake where two wells penetrate 184 ft (well D–423) and 234 ft (well D–2171) of boulder till in what appears to be a former glacial meltwater channel (or col) that breaches the divide between the West Branch Delaware River Basin and the East Branch Delaware River Basin to the south.

Lower West Branch Delaware River

The lower West Branch Delaware River, the 23-mi reach from Walton to Deposit (20 mi to the Cannonsville Reservoir Dam), is the most sinuous of the three reaches and is mostly occupied by the Cannonsville Reservoir. Upstream from the reservoir, the valley fill is characterized by broad outwash terraces overlain by postglacial alluvium. Small kame terraces are emplaced along the valley sides, especially along the inside bends in the river. At Walton, a large remnant outwash terrace occupies the valley between the river and the south valley wall. South of Pinesville, a large kame terrace similarly occupies the sharp inside bend in the river. The Cannonsville Reservoir has covered any glacial deposits that were formerly exposed in this reach. The valley width varies from about 1 mi at Walton to about 3,000 ft at Beerston to about 1,000 ft in the upper reaches of the reservoir. Well data in this reach are sparse, but what data there are indicate that the valley-fill aquifer here varies in thickness from about 70 ft (wells D–261 and D–262) at Walton to more than 60 ft at Pinesville (well D–1150) to a 30-ft-thick aquifer confined beneath 90 ft of lacustrine clay at Beerston (well D–1337). Logs of wells that are located beneath the Cannonsville Reservoir show that the thickness of the valley fill there (as measured from preconstruction land surface altitudes) ranges from 80 ft (well D–105) at the reservoir's eastern end to 125 ft (well D–353) at the former location of the hamlet of Cannonsville approximately 3.5 mi upstream from the dam. The appearance of lacustrine clay, silt, and fine sand in some well logs (well D–403) in the lower section of the West Branch Delaware River valley gives evidence of previous proglacial lakes. The majority of well logs under the Cannonsville Reservoir, however, indicate that the valley fill there is predominantly sand and gravel overlying till (wells D–111 and D–399) or in some locations all till (well D–353). Downstream from the Cannonsville Reservoir, well logs in the valley between the dam and nearby Deposit indicate depths to bedrock ranging from 115 to 150 ft (wells D–284 and D–1570). Logs of wells in this area also indicate thick sequences of fine-grained lacustrine sediments overlain by outwash and underlain by ice-contact sand and gravel. For example, the log of well D–1570 shows 45 ft of outwash sand and gravel overlying 70 ft of fine sand, which grades down into 15 ft of clay, all of which is underlain by 20-ft of basal gravel. Other wells in the area show a similar sequence of outwash overlying lacustrine sediments, all underlain by a thin basal sand and gravel aquifer (wells D–1133, D–1613, D–1797, and D–1832). In some localities, the confined aquifer may be absent.

As in the middle and upper reaches, the valley-fill aquifer in the lower reach of the West Branch Delaware River is very transmissive and is able to support high-yielding municipal supply wells. For example, well D–284 is a 120-ft-deep supply well for Deposit that is screened in the thin, confined basal sand and gravel aquifer and produces 500 gal/min. Three other supply wells, located in adjacent Broome County (BM–452, BM–453, and BM–454), for Deposit similarly have yields ranging from 200 to 500 gal/min.

To summarize, along the main West Branch Delaware River valley, a well drilled anywhere in areas mapped as kame sand and gravel, outwash, or outwash and alluvium on plate 1 (except close to the till-mantled valley walls) is likely to penetrate at least 10 and perhaps 100 ft or more of permeable sand and gravel that could yield 100 gal/min or more to a properly constructed well. In tributary valleys, by contrast, even in areas where kame sand and gravel or alluvium are mapped at land surface, wells are likely to penetrate mostly till above bedrock; highly productive aquifers are uncommon. Maximum long-term aquifer yield to a local array of gravel wells will depend on the availability of infiltration from low flows of the Delaware River and on the volume of water stored in the aquifer, which can be estimated from streamflow records, approximate calculations such as those presented by MacNish and Randall (1982), or from detailed site investigations.

Precipitation, Runoff, and Evapotranspiration

Data from three precipitation stations, one each at Deposit, Walton, and Delhi, were obtained for each year from 2001 to 2010 from the Northeast Regional Climate Center database at Cornell University (http://climod.nrcc.cornell.edu/). The mean annual precipitation for these three stations for the 10-year period was as follows: Deposit, 47.05 in.; Walton, 50.36 in.; and Delhi, 51.90 in. Similarly, the 30-year mean precipitation (1971–2000) for each of these stations was as follows: Deposit, 43.4 in.; Walton, 46.69 in.; and Delhi, 43.20 in. The most recent 10-year precipitation means show an increase in average annual precipitation as one moves upvalley (east) from Deposit to Delhi, while the 30-year mean values show the Walton station as having a higher mean than the other two. The 1971–2000 mean values are similar to slightly higher than values interpolated from the areal distribution of mean annual precipitation over the West Branch Delaware River Basin for 1951–80 (Randall, 1996). Therefore, the contours of mean annual runoff and evapotranspiration depicted in Randall (1996) can still be considered reasonably valid through 2000. The distribution of mean annual precipitation and runoff for 1951–80 within the West Branch Delaware River Basin is shown in figure 7, which shows that the long-term mean annual precipitation ranges from about 44 to 46 in. in the high terrain near the divides that bound the basin on the northwest and southeast, but is close to 43 in. near the axis of the basin (Randall, 1996). Long-term mean annual runoff within the basin ranges from 22 inches per year (in/yr) at the western end of the basin (near Deposit) to 26 in/yr along the southern uplands and in the eastern headwaters (fig. 7). Mean evapotranspiration is approximately 19 in/yr throughout the West Branch Delaware River Basin (Randall, 1996).

Sources of Stream Base Flow

Previous studies of the Beaver Kill Basin (Reynolds, 2000) and the Pepacton Reservoir Basin (Reynolds, 2004) have shown that the streams within these basins exhibit some of the highest base flows in the Catskill Mountain region. A high base flow (that is, dry weather flow) for a stream generally indicates that the basin contains a large amount of groundwater in storage, generally in saturated stratified drift within the valley and (or) in fractured bedrock aquifers. A common statistic that indicates the magnitude of groundwater storage within a given basin is the duration of base-flow recession. Coates (1971) developed base-flow recession curves for 13 stream subbasins in the Delaware River Basin and for 12 stream subbasins in the Susquehanna River Basin and from these curves, calculated two indices to measure the duration of base-flow recession for each stream: (1) the number of days required for flow to decline from its mean annual value to 10 percent of that value and (2) the number of days required for flow to decline from 1 cubic foot per second per square mile [$(ft^3/s)/mi^2$] to 0.1 $(ft^3/s)/mi^2$. Hydrogeologic characteristics for the 13 Catskill Mountain stream subbasins are listed in table 2.

Three stream subbasins gaged by the USGS within the West Branch Delaware River Basin—the West Branch Delaware River near Delhi (01421900), Little Delaware River near Delhi (01422500), and Trout Creek near Trout Creek, N.Y. (0142400103)—were evaluated and are shown in bold typeface in table 2. The two indices of base-flow recession show that all three of these streams have some of the longest base-flow recessions in the Catskill Mountains—33, 28, and 29.7 days, respectively—to decline from 1 $(ft^3/s)/mi^2$ to 0.1 $(ft^3/s)/mi^2$ (table 2). Only four other subbasins—Beaver Kill at Craigie Claire, Beaver Kill at Cooks Falls, Mill Brook, and East Branch Delaware River—display substantially longer base-flow recessions with 37.6, 36.7, 36.1, and 34.7 days, respectively. A long base-flow recession indicates that ground-water is supplying the base flow during long precipitation-free periods. Another commonly used measure of base flow and flow duration is Q_{90}, which is the discharge that is exceeded 90 percent of the time. Values of Q_{90} for the 13 Catskill Mountain subbasins are shown in table 2 in two formats: first as a percentage of mean annual discharge, then as normalized to basin size and expressed as cubic feet per second per square mile. The Q_{90} for the West Branch Delaware River is 8.5 percent of the mean annual discharge, for the Little Delaware River Basin is 7.8 percent of mean annual discharge, and for Trout Creek is 11 percent of mean annual discharge. Similarly, the Q_{90} normalized to basin size is equivalent to 0.145 $(ft^3/s)/mi^2$ in the West Branch Delaware River Basin, 0.141 $(ft^3/s)/mi^2$ in the Little Delaware River Basin, and 0.201 (ft^3/mi^2) in the Trout Creek Basin. These values of Q_{90}, in percent of mean annual discharge and in cubic feet per second per square mile, are similar to or greater than values for the 12 streams evaluated in the Susquehanna River Basin (Coates, 1971), and are similar to 6 other streams in the Delaware River Basin (table 2). These values are, however, substantially less than the Q_{90} values for four streams in the eastern part of the East Branch Delaware River Basin, all of which drain the highest part of the Catskill Mountains, where mean precipitation and runoff

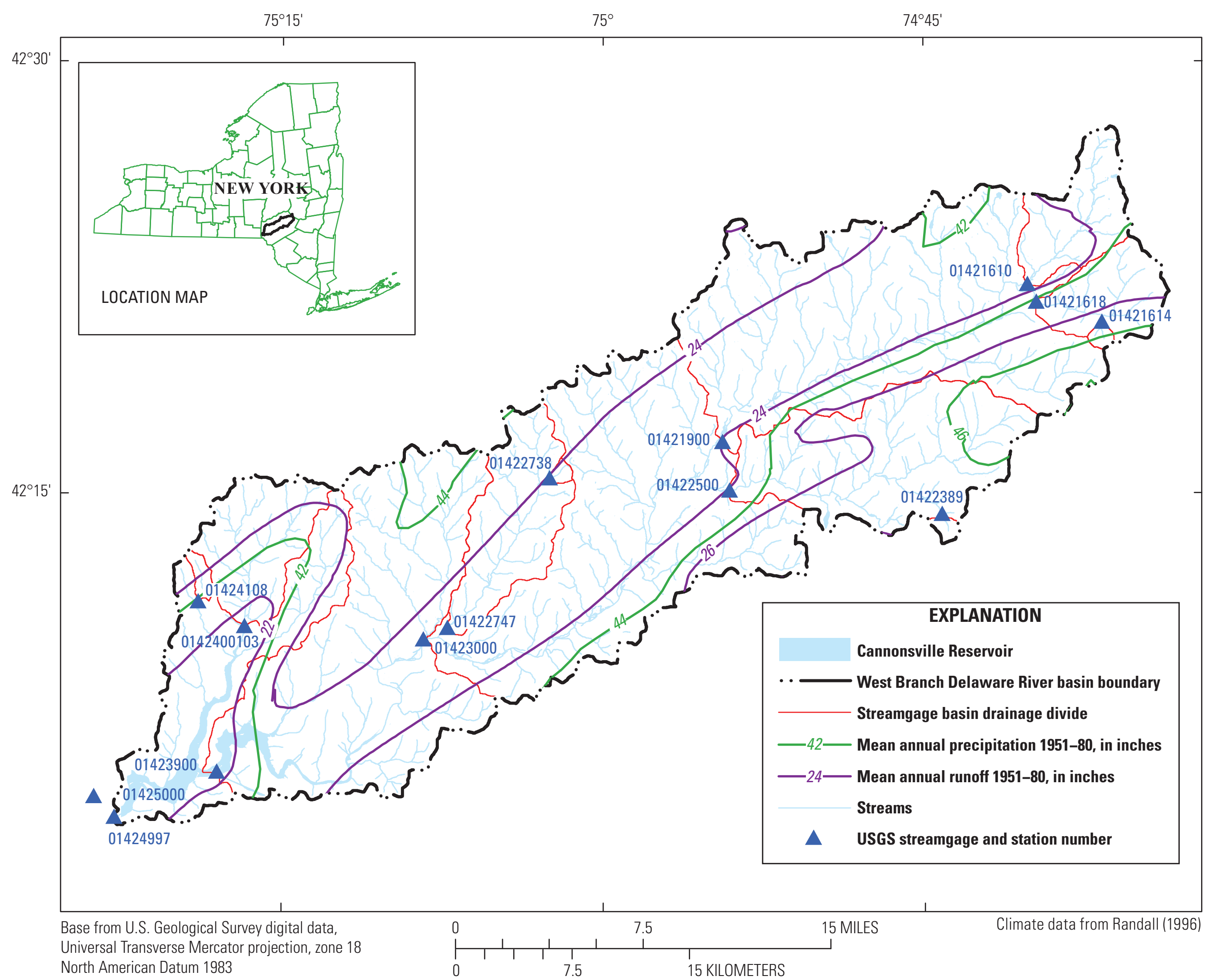

Figure 7. The distribution of mean annual precipitation and runoff for 1951–80 within the West Branch Delaware River Basin.

Table 2. Hydrogeologic characteristics of 13 Catskill drainage basins within the Delaware River Basin in southeastern New York.

[Data are from Coates (1971) and reproduced from Reynolds (2000). Locations are shown in figure 1. Streams within the West Branch Delaware River basin shown in bold typeface. ft, feet; $(ft^3/s)/mi^2$, cubic feet per second per square mile; in., inches; max., maximum; mi^2, square miles; precip., precipitation; Q_{90}, flow at 90 percent duration]

Basin	Basin area, in mi^2	Max. basin relief	Mean annual precip., in in.	Mean annual discharge, in $(ft^3/s)/mi^2$	Flow duration (Q_{90})[†]		Baseflow recession, in days		Area of stratified drift, in percent of basin	Sandstone index,[a] in percent	Massiveness index[b]
					Mean annual discharge, in percent	Normalized to basin size, in $(ft^3/s)/mi^2$	To 10 percent of mean annual discharge	Normalized to decline from 1.0 to 0.1, in $(ft^3/s)/mi^2$			
Terry Clove	14.1	1,290	44.0	1.88	10.0	.188	13.5	16.5	4.3	79	73
Mill Brook	25.0	2,420	48.8	2.27	12.0	.272	26.5	36.1	2.9	91	88
Coles Clove	28.0	1,460	44.0	2.03	10.0	.203	17.7	21.0	5.7	79	73
Tremper Kill	33.0	2,045	43.7	1.88	10.0	.188	13.2	25.2	5.5	88	79
Platte Kill	34.7	2,055	43.0	1.82	9.0	.164	17.7	18.5	4.5	78	71
Trout Creek	**49.5**	**1,280**	**43.4**	**1.83**	**11.0**	**.201**	**22.5**	**29.7**	**7.6**	**78**	**68**
Little Delaware River	**49.8**	**1,965**	**42.7**	**1.81**	**7.8**	**.141**	**22.7**	**28.0**	**3.6**	**64**	**51**
Willowemoc Creek near Livingston Manor*	63	1,960	52.0	2.42	16.0	.387	22.1	32.0	4.4	91	88
Oquaga Creek	66	1,040	43.0	1.78	8.5	.151	17.5	22.9	5.2	84	72
Beaver Kill at Craigie Claire	82	2,495	51.8	2.55	14.0	.357	30.3	37.6	5.0	98	96
West Branch Delaware River	**142**	**1,835**	**41.5**	**1.70**	**8.5**	**.145**	**27.5**	**33.0**	**12.2**	**64**	**53**
East Branch Delaware River	163	2,595	44.0	1.89	10.0	.189	27.1	34.7	5.0	78	70
Beaver Kill at Cooks Falls*	241	2,727	50.1	2.34	16.0	.374	31.5	36.7	6.0	89	82
Mean	76.5	1,930	45.5	2.01	11.0	.228	23.1	28.6	5.5	81	74

[†]Q90 is the stream discharge that is exceeded 90 percent of the time.

[a]Sandstone index is the average percentage of sandstone found within measured stratigraphic sections with each basin (Coates, 1971).

[b]Massiveness index is the percentage of rock units in observable outcrops that exhibit joint-free exposures of greater than 1-ft in thickness (Coates, 1971).

*Includes Willowemoc Creek drainage. Beaver Kill and Willowemoc Creek are treated as separate basins above their confluence at Roscoe, N.Y., and as a combined basin downstream from their confluence.

are much higher than in the West Branch Delaware River Basin (Randall, 1996). The difference in base flows between the West and East Branch Delaware River Basins, therefore, may be related to differences in the percentage of massive sandstone present in each basin and to the corresponding degree of jointing and fracturing of the sandstone (Base Flow in Relation to Geology section).

Base Flow in Relation to Geology

Stream base flows in the glaciated Northeastern United States that are well sustained and (or) that are relatively large in terms of volume per square mile of basin area have generally been ascribed to the discharge of groundwater stored in stratified-drift aquifers that occupy the valley bottoms or to partly saturated ice-contact deposits emplaced against valley walls (Coates, 1971; Randall and Johnson, 1988; Wandle and Randall, 1994; Randall, 2010). Coates (1971) delineated the percentage of land area occupied by stratified drift (valley fill) within each of the13 Catskill Mountain subbasins he studied and found that stratified drift composes 12.2 percent of the West Branch Delaware River Basin, 7.6 percent of the Trout Creek Basin, and 3.6 percent of the Little Delaware River Basin (table 2). The percent area of stratified drift for the West Branch Delaware River Basin is the highest of the 13 Catskill Mountain subbasins studied by Coates (1971), yet it does not display the highest base flow, as measured by both Q_{90} flow duration and the length of base flow recession. The other Catskill Mountain subbasins studied by Coates (1971) in the East Branch Delaware River Basin had lower percentages of stratified drift compared with those of the West Branch Delaware River Basin, but had higher, more sustained base flows (table 2). These findings indicate that most of the base flow in the East Branch Delaware River Basin must be coming from storage in aquifers other than that composed of stratified drift.

Bedrock as a Source of Base Flow

Groundwater discharge from bedrock is a major contributor to stream base flow in Catskill Mountain region streams, particularly in the West Branch Delaware River, East Branch Delaware River, and Beaver Kill subbasins (Coates, 1971; Reynolds, 2000; Reynolds, 2004). Bedrock in the Catskill Mountains consists of sandstone, shale, and siltstone, of which sandstone is the predominant rock type and the most permeable because of its extensive jointing. Coates (1971) developed two indices that describe the amount of sandstone present and the degree of jointing within the sandstone for each of the 13 Catskill Mountain subbasins that he studied (table 2). The first, defined by Coates as the "sandstone index", is the average percentage of sandstone present within measured stratigraphic sections within each subbasin. The second, defined by Coates as the "massiveness index", is a measure of sandstone competency and fabric and is the percentage of rock thickness, as seen in outcrops, in which the spacing between bedding-plane fractures exceeds 1 ft. Coates (1971) observed that the joints in the sandstones of the Catskill Mountains are less numerous but larger and more continuous than those in the shale and siltstone bedrock of the Susquehanna River Basin to the west. He concluded that most of the sandstone within the 13 Catskill Mountain subbasins that he studied is massive and therefore would tend to have large, continuous joints that serve to easily transmit groundwater. The highest sandstone indices of the 13 Catskill Mountain subbasins studied by Coates (1971) were in the Beaver Kill and Willowemoc Creek subbasins (98 percent for the Beaver Kill and 91 percent for Willowemoc Creek); these two subbasins also had the highest massiveness indices (96 percent for the Beaver Kill and 88 percent for Willowemoc Creek) (Reynolds, 2000, table 1).

Among the other East Branch Delaware River subbasins that were analyzed by Coates (1971), the Mill Brook Basin had the highest sandstone index (91 percent) and the highest massiveness index (88 percent); the Tremper Kill Basin had the next highest sandstone and massiveness indices of 88 and 79 percent, respectively (table 2). The remaining four East Branch Delaware River subbasins had sandstone indices of 78 to 79 percent and massiveness indices of 70 to 73 percent (Reynolds, 2000). The high percentage of sandstone in all eight of the East Branch Delaware River subbasins is consistent with the values of Q_{90} as a percent of mean annual discharge, which range from 9 to 12 percent of mean annual discharge (table 2), despite the small amounts of stratified drift within these subbasins—not more than 6 percent, and less than 5 percent in most of the subbasins (Reynolds, 2000, table 1). In comparison, the sandstone indices for the three West Branch Delaware Basins—West Branch Delaware River, Little Delaware River, and Trout Creek—are 64, 64, and 78 percent, respectively, whereas the corresponding massiveness indexes are 53, 51, and 68, respectively. This finding indicates that there appears to be less sandstone bedrock within the West Branch Delaware River Basin compared with the East Branch Delaware River Basin to the south. Furthermore, the overall lower massiveness index for the sandstone in the West Branch Delaware River Basin indicates that the sandstone there appears to be less massive and therefore may have fewer continuous water-bearing joints than does the sandstone in the East Branch Delaware River Basin to the south. Coates (1971) has shown through statistical analysis that the sandstone index and the massiveness index show close correlation with the Q_{90}. Each index was correlated with (1) Q_{90} divided by mean annual discharge and (2) Q_{90} divided by drainage area; the correlation coefficients (R^2) were 0.76 for the sandstone index and 0.79 for the massiveness index, relative to either base-flow term (Coates, 1971, table 6; Reynolds, 2000). This positive relation supports the theory that the sustained base flows in the West and East Branch Delaware River Basins may be wholly or partly derived from groundwater discharge from the jointed-sandstone aquifer, albeit to a greater degree in the East Branch Delaware River Basin. The same conclusion can be said for the adjacent Beaver Kill and Willowemoc Creek Basins to the south (Reynolds, 2000).

Thick Till Deposits as a Possible Source of Base Flow

The thick till that covers many upland areas in the West and East Branch Delaware River Basins could be considered as a potential source of sustained stream base flow, simply because the till covers most of the basin. However, recent studies in New York and New England have shown that the groundwater in thick till deposits does not contribute appreciably to the base flow of streams in glaciated basins. Randall and Johnson (1988) presented four low-flow equations, each one developed from a separate low-flow study in the glaciated Northeastern United States, to estimate the average minimum 7-day low flow, known as the 7Q10. All four equations include independent variables that account for the area covered by stratified drift, the area covered by till, the mean runoff or the mean altitude, and the area occupied by wetlands (Randall and Johnson, 1988, table 1). In each of these studies, the regression coefficients for the area covered by stratified drift was from 9 to 25 times larger than that for the area covered by till. Regression coefficients for stratified drift ranged from 0.46 to 2.16, whereas those for till ranged from 0.05 to 0.10. These small coefficients for till indicate that the till within a basin makes only a minor groundwater contribution to streamflow.

A study by Wandle and Randall (1994) on the effects of surficial geology, lakes, swamps, and annual water availability on the low flows of streams in central New England reached similar conclusions regarding the relative effects of till and stratified drift on base flow. The regression equations developed in that study to estimate 7Q10 for high- and low-relief areas of central New England indicated that groundwater discharge from coarse stratified drift was from 4 to 8 times greater than the groundwater discharge from till. Tills of New England generally have a much lower clay content and, thus, greater permeability than those of New York; this conclusion would imply that the relative amount of groundwater discharged to streams from tills in New York would be much less than in New England.

The results of these Randall and Johnson (1988) and Wandle and Randall (1994) (1) indicate that the thick upland deposits of till within the West and East Branch Delaware River Basins probably contribute little groundwater discharge to the base flow of streams and (2) provide additional evidence that the relatively high base flows of streams in the Catskill Mountain region are at least partly derived from groundwater discharge from the underlying fractured and jointed sandstone.

Summary

In 2009, the U.S. Geological Survey, in cooperation with the New York State Department of Environmental Conservation, began a study of the hydrogeology of the West Branch Delaware River Basin (Cannonsville Reservoir watershed). There has been recent interest by energy companies in developing the natural gas reserves that are trapped within the Marcellus Shale, which is part of the Hamilton Group of Middle Devonian age that underlies all the West Branch Delaware River Basin. Knowing the extent and thickness of stratified-drift (sand and gravel) aquifers within this basin can help State and Federal regulatory agencies to evaluate any potential effects to these aquifers that gas-well drilling might produce.

The West Branch Delaware River Basin (Cannonsville Reservoir watershed) drains about 455 mi^2 of the southwestern Catskill Mountains. The most widespread geologic unit within the basin is till and colluvium, which occurs as masses of ablation till in major stream valleys and as thick deposits of lodgment till and colluvium that partly fill upland basins. Till and colluvium cover approximately 89 percent of the basin, and stratified drift, which consists of alluvium, outwash, and ice-contact deposits, accounts for 8.9 percent. The Cannonsville Reservoir occupies about 1.9 percent of the basin area. Outwash and ice-contact (kame) deposits occupy the West Branch Delaware River valley for its entire 59-mi length from Deposit, New York, to the river's headwaters near Stamford, N.Y. These deposits form a stratified-drift aquifer that ranges in thickness from 40 to 50 feet (ft) in the upper reach of the West Branch Delaware River valley (from Stamford to Delhi, N.Y.), from 70 to 140 ft in the middle reach of the valley (from Delhi to Walton, N.Y.), and from 60 to 70 ft thick in the lower reach of the valley from Walton to Deposit, N.Y. Well yields from the valley-fill aquifer commonly exceed 100 gallons per minute (gal/min) and reach up to 500 gal/min. Thick deposits of lodgment till, some more than 200 ft in thickness, partly fill upland tributary valleys and hollows. The valley train outwash that overlies ice-contact deposits thoughout the basin increases in thickness downvalley from a maximum of 40 ft at Delhi to 50 ft at Walton and to 65 ft at Deposit. Localized deposits of fine-grained lacustrine sediments, up to 100 ft thick, within the valley fill just east of Delhi and southwest of Walton indicate the former locations of proglacial lakes.

The Catskill Mountain series rocks that underlie the West Branch Delaware River Basin are jointed by three distinct joint sets, two vertical joint sets that trend northwestward and northeastward, and a horizontal set that lies parallel to the bedding plane. These joint sets greatly increase the secondary permeability of the rock and thus increase the storage and movement of groundwater within the rock. Yields from bedrock wells completed in the sandstone and shale bedrock within the West Branch Delaware River Basin range from 0 to 400 gal/min, with eight wells having yields in excess of 100 gal/min, and one well having a yield of 400 gal/min. The median yield for 199 bedrock wells completed in Catskill Mountain series rocks in Delaware County is 15 gal/min.

Springs are still an important source of domestic water supply within the West Branch Delaware River Basin, as well as all of Delaware County, and several villages within the West Branch Delaware River Basin use springs as all or part of their municipal supply. The average yield of 178 springs in Delaware County is 8.5 gal/min, with a median yield of 3 gal/min. The highest measured spring yield was 100 gal/min.

The gas-bearing Marcellus Shale underlies the entire West Branch Delaware River Basin, as well as the remainder of Delaware County. Data from 10 deep test holes that encircle the West Branch Delaware River Basin indicate that the Marcellus Shale ranges in thickness from 600 to 650 ft along the northern divide with the adjacent Susquehanna River Basin to about 750 ft thick along the southern divide with the East Branch Delaware River Basin. The depth to the top of the Marcellus Shale ranges from 2,600 to 2,900 ft in two upland tributaries to the adjacent Susquehanna River Basin to 3,240 ft along the northern divide of the West Branch Delaware River Basin, and ranges from 3,500 to 4,150 ft along the southern divide of the West Branch Delaware River Basin.

The long-term mean annual precipitation within the West Branch Delaware River Basin ranges from 42 inches per year (in/yr) at its western end near Deposit to 44 in/yr at the river's headwaters near Stamford, although the average precipitation for the most recent 10-year period (2001–2010) ranged from 47 to almost 52 in/yr. Long-term mean annual runoff within the West Branch Delaware River Basin ranges from 22 in/yr at the western end of the basin to 26 in/yr along the southern uplands and in the eastern headwaters. Long-term evapotranspiration is approximately 19 in/yr throughout the West Branch Delaware River Basin.

Two statistical indicators of base flow, the duration of base-flow recession in days and the discharge that is exceeded 90 percent of the time (Q_{90}), were tabulated and compared for 13 streams in the Catskill Mountain region. Three gaged streams within the West Branch Delaware River Basin displayed base-flow recessions that were longer than those for most streams in the Catskill Mountain region—ranging from 22.5 to 27. 5 days—but were substantially shorter than those for two streams in the Beaver Kill Basin to the south (36.7 and 37.6 days) and for two streams in the adjacent East Branch Delaware River Basin (34.7 and 36.1 days). Similarly, the Q_{90} for the three West Branch Delaware River Basin streams ranged from 7.8 to 11 percent of mean annual discharge, whereas streams in the East Branch Delaware River and Beaver Kill Basins displayed Q_{90} values ranging from 9 to 16 percent of mean annual discharge. Two indices (Coates, 1971) that describe the amount of sandstone present in measurable rock outcrops—the sandstone and massiveness indices—were substantially lower for the three subbasins in the West Branch Delaware River Basin than for subbasins in the adjacent East Branch Delaware River and Beaver Kill Basins to the south. These data support the theory that the sustained base flows in the West and East Branch Delaware River Basins, as well as the Beaver Kill Basin to the south, may be wholly or partly derived from groundwater discharge from the jointed-sandstone aquifer, albeit to a much lesser degree in the West Branch Delaware River Basin.

Selected References

Chadwick, G.H., 1936, History and value of the name "Catskill" in geology: New York State Museum Bulletin No. 307, 116 p.

Coates, D.R., 1966, Glaciated Appalachian plateau-till shadows on hills: Science, v.152, p. 1617–1619.

Coates, D.R., 1971, Hydrogeomorphology of Susquehanna and Delaware basins, *in* Morisawa, Marie, Quantitative geomorphology—Some aspects and applications—Proceedings of the second annual geomorphology symposia series, Binghamton, New York, October 15–16, 1971: Binghamton, N.Y., State University of New York at Binghamton, p. 273–306.

De Witt, Wallace, Jr., Roen, J.B., and Wallace, L.G., 1993, Stratigraphy of Devonian black shales and associated rocks in the Appalachian basin, *in* Roen, J.B., and Kepferle, R.C., eds., Petroleum geology of the Devonian and Mississippian black shale of eastern North America: U.S. Geological Survey Bulletin, 1909–B, p. B1–B57.

Fisher, D.W., Isachsen, Y.W., and Rickard, L.V., 1970, Geologic map of New York: New York Museum and Science Service Map and Chart Series No. 15, 5 sheets, 1:250,000 scale.

Fluhr, T.W., 1953, Geology of New York City's water supply system, a progress report: The Municipal Engineers Journal, v. 39, 4th quarter, p. 125–145.

Fluhr, T.W., and Terenzio, P.E., 1984, Engineering geology of the New York City water supply system: New York State Geological Survey Open-File Report 05.08.001, 184 p.

Gubitosa, Matthew, 1980, Glacial geology of the Hancock area, western Catskills, New York: State University of New York at Binghamton master's thesis, 102 p.

Hely, A.G., and Olmsted, F.H., 1963, Some relations between streamflow characteristics and the environment in the Delaware River region: U.S. Geological Survey Professional Paper 417B, 25 p.

Heisig, P.M., 1999, Water resources of the Batavia Kill basin at Windham, Greene County, New York: U.S. Geological Survey Water Resources Investigations Report 98–4036, 96 p.

Heisig, P.M., 2004, Hydrogeology and water quality of the Pepacton Reservoir watershed in Southeastern New York, part 4 *of* Quantity and quality of ground-water and tributary contributions to stream base flow in selected main-valley reaches: U.S. Geological Survey Scientific Investigations Report 2004–5018, 21 p.

Kipp, J.A., Lawrence, F.W., and Dinger, J.S., 1983, A conceptual model of ground-water flow in the Eastern Kentucky Coal Field, *in* Graves, D.H., ed., Symposium on surface mining, hydrology, sedimentology, and reclamation, Lexington, Kentucky, November 27–December 2, 1983: Lexington, University of Kentucky, p. 543–548.

Kirkland, J.T., 1973, Glacial geology of the western Catskills: State University of New York at Binghamton, Doctoral dissertation, 104 p.

Kirkland, J.T., 1979, Deglaciation events in the western Catskill Mountains, New York: Geological Society of America Bulletin, v.90, p. 521–524.

Koteff, Carl, 1974, The morphologic sequence concept and deglaciation of southern New England, *in* Coates, D.R., ed., Glacial geomorphology: Binghamton, State University of New York Publications in Geomorphology, p. 121–144.

Lash, G.G., and Englander, Terry, 2009, The Middle Devonian Marcellus Shale—A record of eustasy and basin dynamics (abstract and poster), *in* American Association of Petroleum Geologists Annual Meeting, Denver, Colo., June 7–10, 2009: American Association of Petroleum Geologists, accessed 1/20/2011, at http://www.searchanddiscovery.net/documents/2009/090805lash/ndx_lash.pdf.

MacNish, R.D., and Randall, A.D., 1982, Stratified-drift aquifers in the Susquehanna River basin, New York: New York State Department of Environmental Conservation Bulletin 75, 68 p.

Mather, W.W., 1840, Fourth annual report of the geologist of the first geological district of the state of New York, in Fourth annual report: New York Geological Survey, p. 212–258.

Milici, R.C., and Swezey, C.S., 2006, Assessment of Appalachian basin oil and gas resources—Devonian shale—Middle and Upper Paleozoic total petroleum system: U.S. Geological Survey Open File Report 2006–1237, 70 p.

Natural Resources Conservation Service, 1999, Digital soils map of Delaware County, New York: U.S. Department of Agriculture, accessed at *http://soildatamart.nrcs.usda.gov* on 11/2008.

Newland, D.H., and Hartnagle, C.A., 1932, Review of natural gas and petroleum developments in New York State: New York State Museum Bulletin 295, p. 101–184.

New York State Department of Health, 1982, New York State atlas of community water system sources: New York State Department of Health, 79 p.

Ozvath, D.L., 1985, Glacial geomorphology and late Wisconsinan deglaciation of the western Catskill Mountains, New York: State University of New York at Binghamton doctoral dissertation, 181 p.

Ozvath, D.L., and Coates, D.R., 1986, Woodfordian stratigraphy in the western Catskill mountains, *in* Cadwell, D.H., The Wisconsinan stage of the first geologic district, eastern New York: New York State Museum Bulletin No. 455, p. 109–120.

Parker, G.G., Hely, A.G., Keighton, W.B., Olmsted, F.H., and others, 1964, Water resources of the Delaware River basin: U.S. Geological Survey Professional Paper 381, 200 p.

Parker, J.M., III, 1942, Regional systematic jointing in slightly deformed sedimentary rocks: Geological Society of America Bulletin v. 53, p. 381–408.

Randall, A.D., 1996, Mean annual runoff, precipitation, and evapotranspiration in the glaciated northeastern United States, 1951–80: U.S. Geological Survey Open-File Report 96–395, 2 sheets, scale 1:1,000,000.

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.

Randall, A.D., 2010, Low flow of streams in the Susquehanna River basin of New York: U.S. Geological Survey Scientific Investigations Report 2010–5063, 57 p.

Randall, A.D., and Johnson, A.I., 1988, The northeast glacial aquifers RASA project—An overview of results through 1987, *in* Randall, A.D., and Johnson, A.I., eds., Regional aquifer systems of the United States-the northeast glacial aquifers: American Water Resources Association Monograph Series no. 11, p. 1–15.

Reynolds, R.J., 2004, Hydrogeology and water quality of the Pepacton Reservoir watershed in southeastern New York—Part 2. Hydrogeology, stream base flow, and groundwater recharge: U.S. Geological Survey Scientific Investigations Report 2004–5134, 31p.

Reynolds, R.J., 2000, Hydrogeology of the Beaver Kill basin in Sullivan, Delaware, and Ulster counties, New York: U.S. Geological Survey Water Resources Investigations Report 00–4034, 23 p.

Rich, J.L., 1935, Glacial geology of the Catskills: New York State Museum Bulletin no. 299, 180 p.

Rickard, L.V., 1975, Correlation of the Silurian and Devonian rocks in New York State: New York State Museum and Science Service Map and Chart Series no. 24, 16 p.

Soder, D.J., and Kappel, W.M., 2009, Water resources and natural gas production from the Marcellus Shale: U.S. Geological Survey Fact Sheet 2009–3032, 6 p.

Soren, Julian, 1963, The ground-water resources of Delaware County, New York: New York State Department of Conservation Bulletin GW–50, 59 p.

Ver Straeten, C.A., Griffing, D.H., and Brett, C.E., 1994, The lower part of the Middle Devonian Marcellus "Shale", central to western New York State; stratigraphy and depositional history, *in* Brett, C.E., and Scatterday, James, eds., Field trip guidebook: New York State Geological Association Guidebook, 66th Annual Meeting, Rochester, N.Y., p. 271–321.

Wandle, S.W., and Randall, A.D., 1994, Effects of surficial geology, lakes and swamps, and annual water availability on low flows of streams in central New England, and their use in low-flow estimation: U.S. Geological Survey Water Resources Investigations Report 93–4092, 57 p.

Williams. J. H., 2010, Evaluation of well logs for determining the presence of freshwater, saltwater, and gas above the Marcellus Shale in Chemung, Tioga, and Broome Counties, New York: U.S. Geological Survey Scientific Investigations Report 2010–5224, 27 p.

Woodward, H.P., 1957, Structural elements of the northeastern Appalachians: American Association of Petroleum Geologists Bulletin, v. 41, no. 7, p. 1429–1440.

Wyrick, G.G., and Borchers, J.W., 1981, Hydrologic effects of stress-relief fracturing in an Appalachian valley: U.S. Geological Survey Water Supply Paper 2177, 51 p.

Prepared by the Pembroke Publishing Service Center.

For more information concerning this report, contact:

Director
U.S. Geological Survey
New York Water Science Center
425 Jordan Road
Troy, NY 12180-8349
dc_ny@usgs.gov

or visit our Web site at
http://ny.water.usgs.gov

USGS

Reynolds—**Hydrogeology of the West Branch Delaware River Basin, Delaware County, New York**—Scientific Investigations Report 2013–5025