In cooperation with
NEW YORK STATE DEPARTMENT OF ENVIRONMENTAL CONSERVATION

Hydrogeology and Water Quality of the Pepacton Reservoir Watershed in Southeastern New York

Part 2. Hydrogeology, Stream Base Flow, and Ground-Water Recharge

Scientific Investigations Report 2004-5134

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

Cover: Ground water discharging from a contact spring exposed in a roadcut of Catskill Mountain Series rocks (Upper Walton Formation), Ulster County, N.Y. Springs 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.)

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Gale A. Norton, Secretary

U.S. Geological Survey
Charles G. Groat, Director

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For additional information about this report write to:
U.S. Geological Survey
425 Jordan Road
Troy, NY 12180
Email: askny@usgs.gov
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Multiply	By	To obtain
Length		
inch (in.)	2.54	centimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
foot per mile (ft/mi)	0.1894	meter per kilometer
Area		
square mile (mi^2)	2.590	square kilometer
Flow rate		
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per second (ft^3/s)	28.32	liter per second
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
gallon per day per square mile [$(gal/d)/mi^2$]	0.001461	cubic meter per day per square kilometer
million gallons per day (Mgal/d)	0.04381	cubic meter per second
million gallons per day (Mgal/d)	3,785	cubic meters per day
million gallons per day per square mile [$(Mgal/d)/mi^2$]	1,461	cubic meter per day per square kilometer
gallons per day per square mile [$(gal/d)/mi^2$]	0.001462	cubic meters per day per square kilometer
gallon per day per foot [(gal/d)/ft]	0.0001437	liter per second per meter
Hydraulic Units		
transmissivity, feet squared per day (ft^2/d)	0.0929	meter squared per day
hydraulic conductivity*, feet per day (ft/d)	0.3048	meter per day
specific capacity, gallons per minute per foot (gal/min)/ft	0.2070	liter per second per meter
pound per cubic foot (lb/ft^3)	0.01602	gram per cubic centimeter

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29); horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27).

* Hydraulic conductivity: The standard unit for hydraulic conductivity is cubic foot per day per square foot of aquifer cross-sectional area ($ft^3/d/ft^2$. In this report, the mathematically reduced form, feet per day (ft/d) is used for convenience.

Hydrogeology and Water Quality of the Pepacton Reservoir Watershed in Southeastern New York

Part 2. Hydrogeology, Stream Base Flow, and Ground-water Recharge

By Richard J. Reynolds

Abstract

The hydrogeology of the 372-square-mile Pepacton Reservoir watershed (herein called the East Branch Delaware River Basin) in the southwestern Catskill Mountain region of Southeastern New York is described and depicted in a detailed surficial geologic map and two geologic sections. An analysis of stream discharge records and estimates of mean annual ground-water recharge and stream base flow for eight subbasins in the basin are included.

Analysis of surficial geologic data indicates that the most widespread geologic unit within the basin is till, which occurs as masses of ablation till in major stream valleys and as thick deposits of lodgment till that fill upland basins. Till covers about 91.5 percent of the Pepacton Reservoir watershed, whereas stratified drift (alluvium, outwash, and ice-contact deposits) accounts for 6.3 percent. The Pepacton Reservoir occupies about 2.3 percent of the basin area. Large outwash and ice-contact deposits occupy the valleys of the upper East Branch Delaware River, the Tremper Kill, the Platte Kill, the Bush Kill, and Dry Brook. These deposits form stratified-drift aquifers that range in thickness from 90 feet in parts of the upper East Branch Delaware River Valley to less than 30 feet in the Dry Brook valley, and average about 50 feet in the main East Branch Delaware River Valley near Margaretville.

An analysis of daily mean stream discharge for the six eastern subbasins for 1998-2001, and for two western subbasins for 1945-52, was performed using three computer programs to obtain estimates of mean annual base flow and mean annual ground-water recharge for the eight subbasins. Mean annual base flow ranged from 15.3 inches per year for the Tremper Kill subbasin to 22.3 inches per year for the Mill Brook subbasin; the latter reflects the highest mean annual precipitation of all the subbasins studied. Estimated mean annual ground-water recharge ranged from 24.3 inches per year for Mill Brook to 15.8 inches per year for the Tremper Kill. The base flow index, which is the mean annual base flow expressed as a percentage of mean annual streamflow, ranged from 69.1 percent for Coles Clove Kill to 75.6 percent for the upper East Branch Delaware River; most subbasin indices were greater than 70 percent. These high base flow indices indicate that because stratified drift covers only a small percentage of subbasin areas (generally 5 to 7 percent), most of the base flow is derived from the fractured sandstone bedrock that underlies the basin.

Introduction

The Pepacton Reservoir watershed, which is composed of the upper reaches of the East Branch Delaware River Basin, encompasses a drainage area of approximately 372 mi^2 in the Catskill Mountain region of Southeastern New York. The location of the East Branch Delaware River Basin and its eight subbasins are shown in figure 1.

Most productive aquifers in Upstate New York consist of stratified-drift (unconsolidated) deposits of sand and gravel that occupy major river and stream valleys. In the Catskill Mountain region of New York, these aquifers occupy narrow, steep-walled valleys and are typically underlain or overlain by large thicknesses of till. Many small municipalities, individual residences, and non-municipal community water systems withdraw ground water from these aquifers for domestic and public supply. Stratified-drift aquifers occupy eight major subbasins within the East Branch Delaware River Valley and supply ground water to the villages of Margaretville and Fleishmanns (fig. 1), and to the Roxbury and Arkville Water Districts, which have a combined population of 2,200. In addition, ground water in most of these aquifers is hydraulically connected to streams or rivers within these valleys and is discharged to streams during periods of little or no precipitation to sustain stream base flow.

Knowing the location, extent, and potential for ground-water development of these stratified-drift aquifers is an important first step toward managing the ground-water resources of this region. In 2000, the U.S. Geological Survey

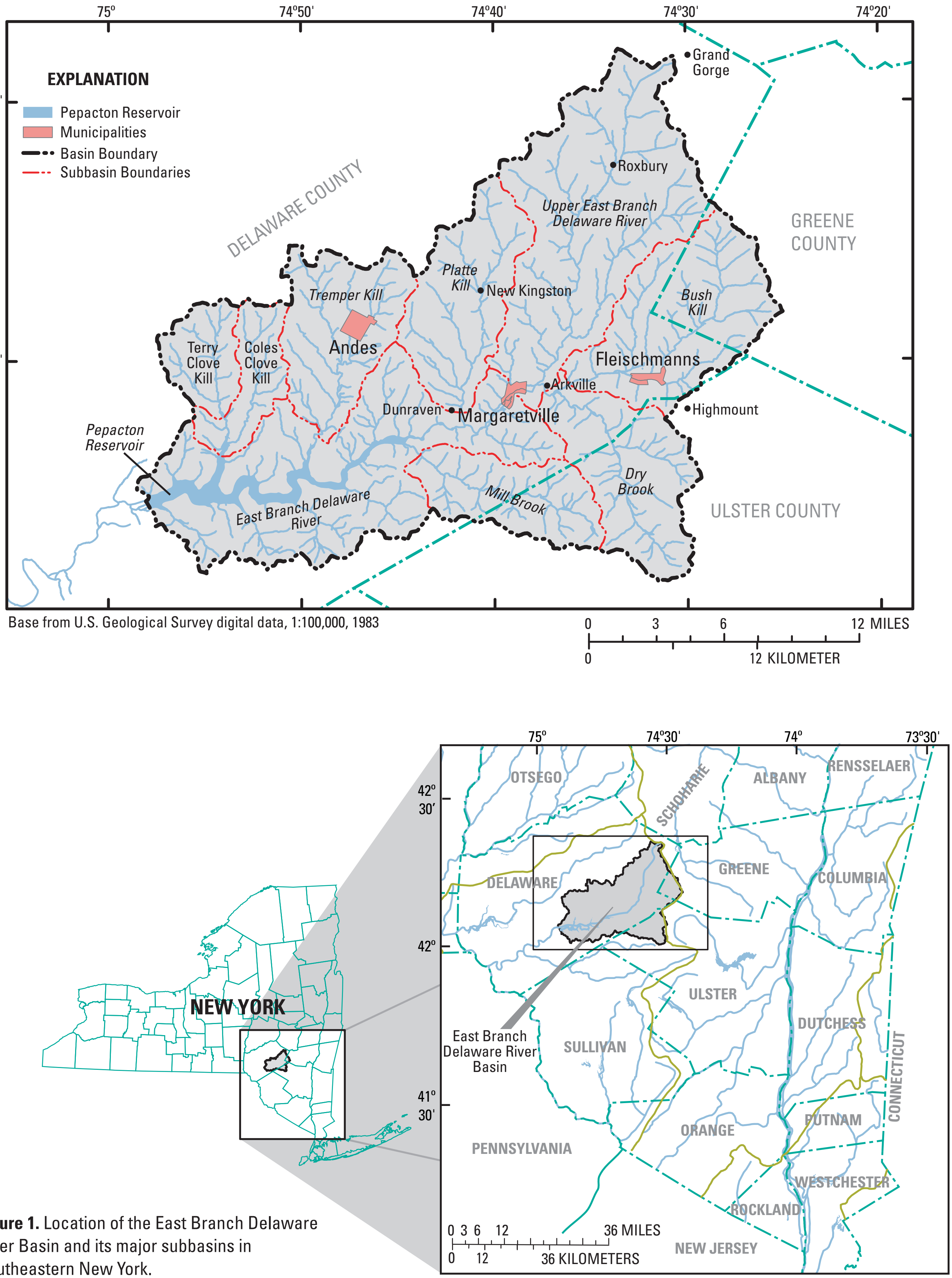


Figure 1. Location of the East Branch Delaware River Basin and its major subbasins in Southeastern New York.

(USGS), in cooperation with the New York State Department of Environmental Conservation, began a multi-phase study of the hydrology of the Pepacton Reservoir watershed that entailed delineating the extent of stratified drift aquifers within the basin, conducting a survey of pesticides and herbicides in ground water and surface water, and conducting a general water-quality assessment of ground water and surface water in the basin. The results of these studies are being published as four separate reports: part 1 (Phillips and Heisig, 2004) gives concentrations of pesticides and their degredates in stream base flow from 2000-2001; part 3 (Heisig and Phillips, 2004) describes the responses of stream base-flow chemistry to hydrogeologic factors and non-point sources of contamination; and part 4 (Heisig, 2004) describes the quantity and quality of ground water and tributary contributions to stream base flow in selected main-valley reaches. This report, part 2 (Reynolds, 2004), describes the hydrogeology and extent of stratified-drift aquifers within the basin and gives estimates of mean annual base flow and recharge in each subbasin.

Objectives and Approach

The primary objective of this phase of the study was to map the distribution of the stratified-drift aquifer systems in the East Branch Delaware River valley above the Pepacton Reservoir — within Delaware, Ulster, and Greene Counties — and produce a digital 1:48,000-scale map of the surficial geology of the basin. The mapped area consists of all or part of thirteen 7.5- minute quadrangles and covers an area of 372 mi^2. The map was derived from four sources: (1) reconnaissance-level mapping of surficial geology at 1:24,000 scale, on file with the New York State Geological Survey; (2) maps and illustrations from unpublished doctoral dissertations by Kirkland (1973) and Ozvath (1985); (3) unpublished reconnaissance-level surficial geologic maps at 1:62,500 scale, prepared during a previous USGS study of the ground-water resources of Delaware County (Soren, 1958, 1963); and (4) soils maps of Delaware County produced by the Natural Resources Conservation Service of the U.S. Department of Agriculture. Surficial geology was compiled at 1:24,000 scale; the mapping included upland areas that are adjacent and tributary to the main valley-fill aquifers. A secondary objective was to provide estimates of average annual base flow and recharge to each of the subbasins within the East Branch Delaware Basin; this was accomplished through an analysis of daily mean stream discharge using computer programs developed by Rutledge (1993).

Purpose and Scope

This report contains two major sections. The first (1) outlines the deglacial chronology that led to the deposition of major morphostratigraphic units, (2) describes the distribution and character of surficial geologic units within the East Branch Delaware River Basin and its subbasins, (3) describes the general stratigraphy and hydrogeology of the bedrock that underlies the basin and, (4) discusses the approximate thickness and character of stratified-drift aquifers within the six largest subbasins. The second part (1) describes the computation of mean annual base flow and ground-water recharge through automated hydrograph separation procedures for the period 1998-2001, (2) presents mean annual precipitation, recharge, and base flow estimates by subbasin for the period 1998-2001, and (3) discusses the relation of stream base flow in the subbasins to bedrock and surficial geology.

Previous Studies

Several investigators have studied various hydrologic and geologic aspects of the East Branch Delaware River Basin. Rich (1935) studied the surficial geology of the western and central Catskills, including the eastern half of the East 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 East Branch Delaware River Basin, whereas Ozvath’s study included only the westernmost part of the basin.

Investigations by the USGS in the 1950’s and early 1960’s, in cooperation with the New York State Department of Conservation, produced reports on the ground-water resources of Delaware (Soren, 1963) and Greene (Berdan, 1954) Counties, which contain most of the East Branch Delaware River Basin. Geotechnical and engineering studies conducted by the New York City Board of Water Supply from the 1930’s through the 1940’s, in conjunction with the planned construction of the Pepacton Reservoir, provided various unpublished memoranda reports describing the results of test borings at planned dam sites (for example, Bird and Berkey, 1944) and two published summary reports (Fluhr, 1953; Fluhr and Terenzio, 1984). Perlmutter and Salvas (Perlmutter, N.M., and Salvas, E.H., U.S. Geological Survey, written commun., 1957) described various aspects of ground water 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 1960’s 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 Catskill and Susquehanna River Basin streams by Coates (1971) investigated the relation of bedrock type and joint spacing to stream base flow, and provided streamflow and low-flow statistics for all gaged streams in the Delaware River Basin in New York. Reynolds (2000) delineated the surficial geology of the Beaver Kill basin to the south, and suggested a relation between the permeability of Catskill Mountain Series sandstones and the high stream base flows within that basin.

Hydrogeology

The thickness, type, and areal extent of surficial geologic units within the East Branch Delaware River Basin are the direct result of the mode of deglaciation that occurred there, and are among the principal factors that determine the ground-water availability within the basin and the amount and distribution of ground water and surface runoff to the eight subbasins within the Pepacton Reservoir watershed.

Deglaciation of the East Branch Delaware River Basin

The style of deglaciation that occurred in the East Branch Delaware River Basin resulted in the emplacement of numerous deposits of ice-contact stratified drift and large masses of ablation till, particularly in the upland tributary valleys. The mode of deglaciation in the East Branch Delaware differed from that in the West Branch, primarily because of the steepness of the valley walls combined with the sinuosity of the East Branch Delaware River (Kirkland, 1979). Ice retreat in the valley of the West Branch 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 display three or four fluvial morphosequences (Koteff, 1979), 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, 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 Valley, downstream of the present study area. Kirkland (1979) identified three glacial-lake stages that he named after the locations of the ice dams that produced them: the Harvard Lake Stage, at 1,099 ft above NGVD 29; the Shinhopple Lake Stage, at 1,161 ft; and the Shavertown Lake Stage, at 1,299 ft. These proglacial lake stages are evidenced by numerous kame deltas along lower East Branch valley walls, and by well logs that show deposits of lacustrine silt and clay in the lower East Branch Valley, below the Downsville dam.

Deglaciation in the East Branch Delaware River Basin began with the mass stagnation of ice within the adjacent Beaver Kill and Willowemoc Creek valleys to the south. The ice sheet then thinned over the southern escarpment (the divide between the East Branch Delaware and the Beaver Kill Basins) and ablated to the extent that large masses of stagnant ice in the lower East Branch Valley, southeast of Shinhopple, began to melt. During this time, the Harvard Lake Stage (1,099 ft) was formed by an ice dam at Harvard and extended an unknown distance up the East Branch Delaware Valley. This lake, and the two successive lake stages — Shinhopple at 1,161 ft, and Shavertown at 1,299 ft — received meltwater from the active ice margin to the north, through cols and notches in the divide between the East and West Branches of the Delaware Valley (Ozvath and Coates, 1986). As the active ice retreated upvalley past Shavertown, both the Harvard and Shinhopple Lake stages drained, as evidenced by kame-terrace deposits in several southward-flowing tributaries grading to outwash in the lower East Branch Delaware River Valley (Ozvath and Coates, 1986). Both of these lake stages produced kame deltas at several locations in the main East Branch Delaware valley southwest of the Downsville dam, and small, discontinuous deposits of lacustrine silt and sand in the main valley, as seen in test borings for the Downsville dam (fig. 3, section A-A’). The third and highest lake level (1,299 ft above NGVD 29) was formed by an ice dam near the now-extinct hamlet of Shavertown, which was demolished during the construction of the Pepacton Reservoir. The hamlet was located at a sharp southward bend in the East Branch Delaware River near the mouth of the Tremper Kill. Evidence of this lake is seen as a kame delta along the southern valley wall just northeast of Arena (fig. 2), that grades to the 1,299-ft lake elevation. The extent of the Shavertown lake stage is unknown, however, the present stream grade indicates that it probably extended upstream to near Margaretville. These three glacial lakes were relatively small in size and short-lived when compared to regional glacial lakes such as Glacial Lake Albany because: (1) relatively little fine-grained lacustrine material appears in the logs of test borings or wells within the valley, (2) drainage in the main East Branch Delaware River Valley and its tributaries was away from the retreating ice; thus, the only dams that could have impounded lake water would have to have consisted of either morainic material or detached ice blocks, and (3) if detached ice blocks were the temporary dams, they would not have lasted long (probably tens of years) in an ice-ablation climate.

Ozvath and Coates (1986) note that the steep valley walls and sinuosity of the East Branch Delaware River would have caused much larger bodies of stagnant ice to persist here than in the West Branch, and the long time needed for these large bodies of stagnant ice to ablate, allowed a variety of ice-contact depositional features to develop in the East Branch valley. This ice-stagnation mode of glacial retreat is the reason why all principal morphostratigraphic units that occupy the southward draining tributaries to the East Branch Delaware River are ice-contact deposits (kames, kame terraces, kame moraines), deposited by glacial meltwater against stagnant ice. These detached and ablating ice masses in these tributaries were also the source of large amounts of ablation till that were deposited in the valley bottoms, through the melt-out of englacial and supraglacial debris. Ozvath (1985) notes that, in many parts of these tributary valleys, exposures of ablation till grade almost imperceptibly into the stratified drift of kame moraines or kame terraces.

When all of the ablating ice masses had melted in the East Branch Delaware River Valley, and the ice front was well north of the East Branch Delaware River Basin, glacial meltwater from glacial Lake Grand Gorge (Rich, 1935), which occupied the Schoharie Valley to the east, began to cascade through the bedrock notch at Grand Gorge (fig. 2), at an elevation of 1,600 ft above NGVD 29, and flow into the head of the upper East Branch Delaware River Valley. Glacial Lake Grand Gorge was not an open-water lake at that time but, rather, was partly filled with stagnant glacial ice (Cadwell, 1986). Meltwater flowed around and across this ice toward the Grand Gorge outlet until another, lower, drainage channel —the Franklinton Channel at 1,200 ft. — became ice free. The opening of the Franklinton Channel allowed glacial Lake Grand Gorge to drain northward through this outlet to Catskill Creek and then eastward to the Hudson Valley. The large volumes of meltwater flowing through the Grand Gorge outlet and into the East Branch Delaware River Valley caused erosion and resedimentation of the ice-contact and till deposits within the valley, and also transported large amounts of sediment from outside the basin divide. As a result, the upper East Branch Delaware now contains the eroded remnants of kame terraces and a well-developed valley train of outwash overlain by post glacial alluvium throughout its upper reach.

Because the Upper East Branch Delaware was linked to, and received drainage from a saddle (Grand Gorge) in the northern basin divide it is the primary reason that this subbasin contains more outwash and ice-contact sand and gravel than any other subbasin in the East Branch Delaware River Basin. Randall (2001) points out that the valleys in rugged terrain in the glaciated Northeast that were connected by the lowest elevation cols or saddles apparently became trunk drainage systems during deglaciation, and therefore conveyed much larger volumes of meltwater and sediment than did other parallel or transverse valleys. Moreover, coarse sand-and-gravel outwash in these trunk drainage valleys is likely to be thicker, better sorted, and more continuous than in the intervening or adjacent valleys in which less meltwater was available (Randall, 2001). The relations between streams in the East Branch Delaware River Basin, saddles in the drainage divides, and remarks on glacial meltwater flows are summarized in Table 1.

Many of the subbasins had no inlet for meltwater drainage from outside the basin divide; nevertheless these subbasins contain extensive deposits of outwash and alluvium (fig. 2). For example, the subbasins of Mill Brook, Dry Brook, Platte Kill, Bush Kill, and Terry Clove contain detached segments of outwash on the valley floor, separated by deposits of ice-contact sand and gravel or till, even though these subbasins could not have received exterior meltwater drainage (table 1). In these valleys, glacial ice probably became detached, then stagnated and melted in place at nearly the same time as ice in adjacent valleys, and internal drainage developed within the decaying ice to form a system of tunnels and (or) crevasses. The stagnant ice deposited much of its sediment load as ablation till or ice-contact deposits, and mass movements over the next several hundred years of post-glacial climate carried sediment to late-deglacial streams that deposited alluvium along the floors of these valleys. These deposits, although mapped as outwash are, therefore, largely of late-deglacial to postglacial in origin.

Surficial Geology

The primary objective of this study was to produce a generalized surficial geologic map of the East Branch Delaware River Basin above the Downsville dam that can be used to identify the location and extent of stratified-drift (sand and gravel) aquifers within the drainage area of the Pepacton Reservoir. The surficial geologic map (fig. 2) includes all or part of thirteen 7.5-minute quadrangles and represents an area of 372 mi^2. The map is based on the interpretation of surficial units as depicted in four sources: (1) unpublished reconnaissance-level surficial geologic maps by D. H. Cadwell, at 1:24,000 scale, on file with the New York State Geological Survey; (2) plates and illustrations in doctoral dissertations by Kirkland (1973) and Ozvath (1985); (3) unpublished reconnaissance-level surficial geologic maps at 1:62,500 scale, prepared as part of a previous USGS study by Soren (1963), and (4) digital soils maps of Delaware County produced by the Natural Resources Conservation Service (NRCS) in Walton, N.Y.

During map compilation, morphostratigraphic units delineated either by Cadwell (1998), Kirkland (1973), or Ozvath (1985) in valley sections were compared with each other and with field notes and observations made by Soren (1958). Generally, the contacts of morphostratigraphic units delineated by Cadwell, Kirkland, or Ozvath were retained or were modified slightly. Areas of thick lodgment till (greater than 5 ft) in upland valleys were delineated by overlaying the NRCS digital soils data onto 1:24,000 topographic maps, then comparing the distribution of soils units derived from till parent material to the topography, using breaks in slope as a guide for delineating geologic contacts.

Surficial Geologic Units

The four major types of surficial (unconsolidated) sediments within the East 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 (fig. 2) as three distinct units: thin till (ground moraine), thick 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 East Branch Delaware River Valley and some of its larger tributaries. Outwash and postglacial alluvium form a narrow deposit of coarse gravel and sand that floors the East 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 is the predominant surficial geologic unit within the East Branch Delaware River Basin and covers approximately 91.5 percent of the area within the basin. Till occurs within the

Table 1. Ranking of subbasins in the East Branch Delaware River Basin in Southeastern New York with respect to potential for glacial meltwater inflow across saddles on drainage divides. [Locations shown on fig. 2; ft, feet]

Stream subbasin	Drainage saddle and elevation	Remarks
Upper East Branch Delaware River	Grand Gorge, 1600 ft above NGVD 29.	Lowest saddle anywhere on the Delaware-Mohawk divide. Likely to have carried substantial meltwater flow throughout deglaciation.
Tremper Kill	Lake Delaware-Bigger Hollow, 1,830 ft.	The lowest saddle on the divide between the East and West Branch Delaware Basins, and adjoins the large valley of the Little Delaware River. Prolonged meltwater flow across the divide during deglaciation is more likely here than in any other tributary subbasin.
Bush Kill/Emory Brook	Highmount, 1,890 ft.	Saddle opens to the southeast, to head of stream draining to Big Indian on Esopus Creek. Not clear if there was any flow or which direction meltwater would have flowed.
Bush Kill/Vly Brook	Mountaintop ridge, no saddle	No remarks.
Terry Clove Kill	Saddle at 1,910 ft.	Lack of major valley to north precludes any meltwater flow across divide.
Coles Clove Kill	Saddle at 2,190 ft at head of Falls Clove Kill tributary.	Lack of major valley to north precludes any meltwater flow across divide.
Platte Kill	Winter Creek saddle at 2,450 ft. Bryant Creek saddle at 2,210 ft. All other tributaries head in mountaintop ridges, no saddles.	Lack of major valley to north of Winter Creek saddle precludes any meltwater flow across divide. Bryant Creek saddle breaches divide with adjacent Tremper Kill, not towards any retreating ice.
Dry Brook	Mountaintop ridge, no saddle	North-draining tributary. No possibility of meltwater flow into this subbasin.
Mill Brook	Mountaintop ridge, no saddle.	North-draining tributary. No possibility of meltwater flow into this subbasin.

basin as: (1) thin till (ground moraine), (2) thick till of varying origins, and (3) colluvium, which is till that has moved downslope and has been redeposited. The predominance of till in the East Branch Delaware 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 East Branch Delaware River Basin progressed as “ice-stagnation retreat”, which resulted in the deposition of large amounts of ablation till in the valley bottoms (Kirkland, 1973; Ozvath, 1985). Ozvath (1985) refers to the 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 Catskills 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, and which resulted in wide variability in till composition (Ozvath, 1985). The ablation till in the western Catskills 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 (Ozvath, 1985).

Thick deposits of ablation till in the East Branch Delaware River Basin, and in much of the western Catskills, form a variety of recognizable landforms, such as drumlinlike 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 such features as ablation till 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 valleys tributary to the East Branch Delaware River, as well as many other streams in the western Catskills, 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). 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 Catskills and noted that the till in the lee 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 (1971) 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) notes that thick till shadows that locally protrude into valley bottoms in the Catskills 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 ablation till are presumably of small areal extent, and may or may not be hydraulically connected to the surficial outwash aquifer that underlies most of the valleys in the Catskills.

Some of the thickest deposits of till in the East Branch Delaware Basin are deposits of lodgment till that fill upland bedrock valleys and hollows in the headwaters of upland tributaries. These deposits are the result of ice movement over the divides that separate the East Branch Delaware River Basin from the Schoharie Creek and West Branch Delaware River Basins, and 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, it is deposited as a veneer of ground moraine that generally does not exceed 6 ft in thickness. Lodgment till and ground moraine in the East 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).

Colluvium

Colluvium is one of the major surficial geologic units in the East Branch Delaware River Basin and covers about 1.2 percent of the basin (fig. 2). It is prevalent in the steep-sloped, southward draining Platte Kill and Batavia Kill, as well as along the southern wall of the East Branch Delaware River southwest of Margaretville. Ozvath (1985) lists three types of colluvium common to the western Catskills: (1) remobilized till, (2) talus, and (3) landslide. Remobilized till forms gently sloping, hummocky deposits at the base of steep hillsides and is derived from lodgment till that has moved gradually downslope through gravity during periglacial conditions. Talus consists of angular, boulder-sized slabs of local bedrock that became dislodged from 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 a corresponding concave depression in the hillside, directly upslope, 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 alter the course of the modern-day stream. Colluvium that is composed of remobilized till can cover and obscure older sand-and-gravel deposits on the valley floor and locally confine ground water in the underlying aquifer.

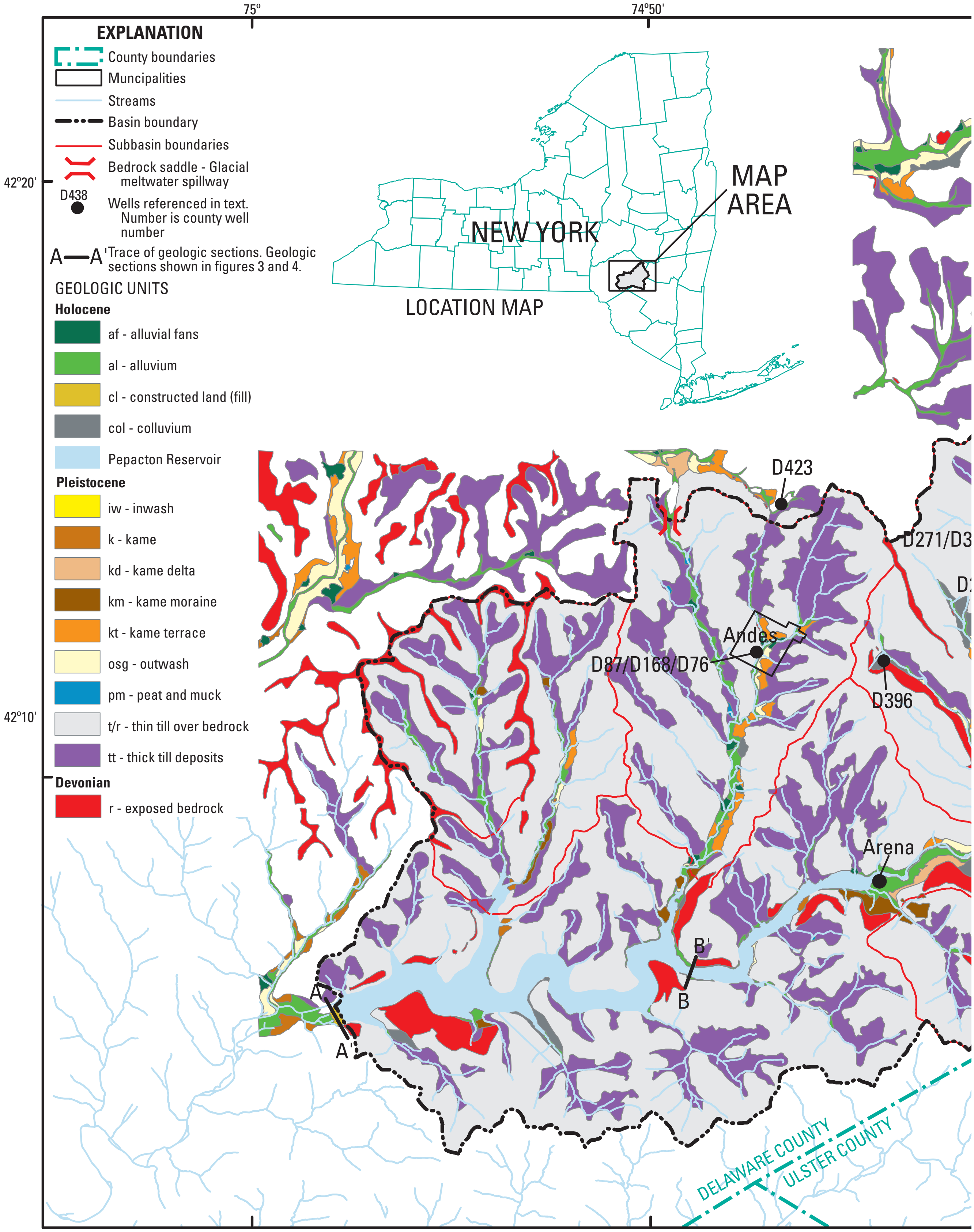
Ice-contact stratified drift

Geomorphic features within the East Branch Delaware River Basin that consist of ice-contact stratified drift include kames, kame terraces, kame deltas, and kame moraines. These units (fig. 2) are closely associated with, and commonly interfinger with, adjacent or nearby deposits of ablation till. Most of these deposits are along the valleys of the main East Branch Delaware River and its southward-draining tributaries.

Kames

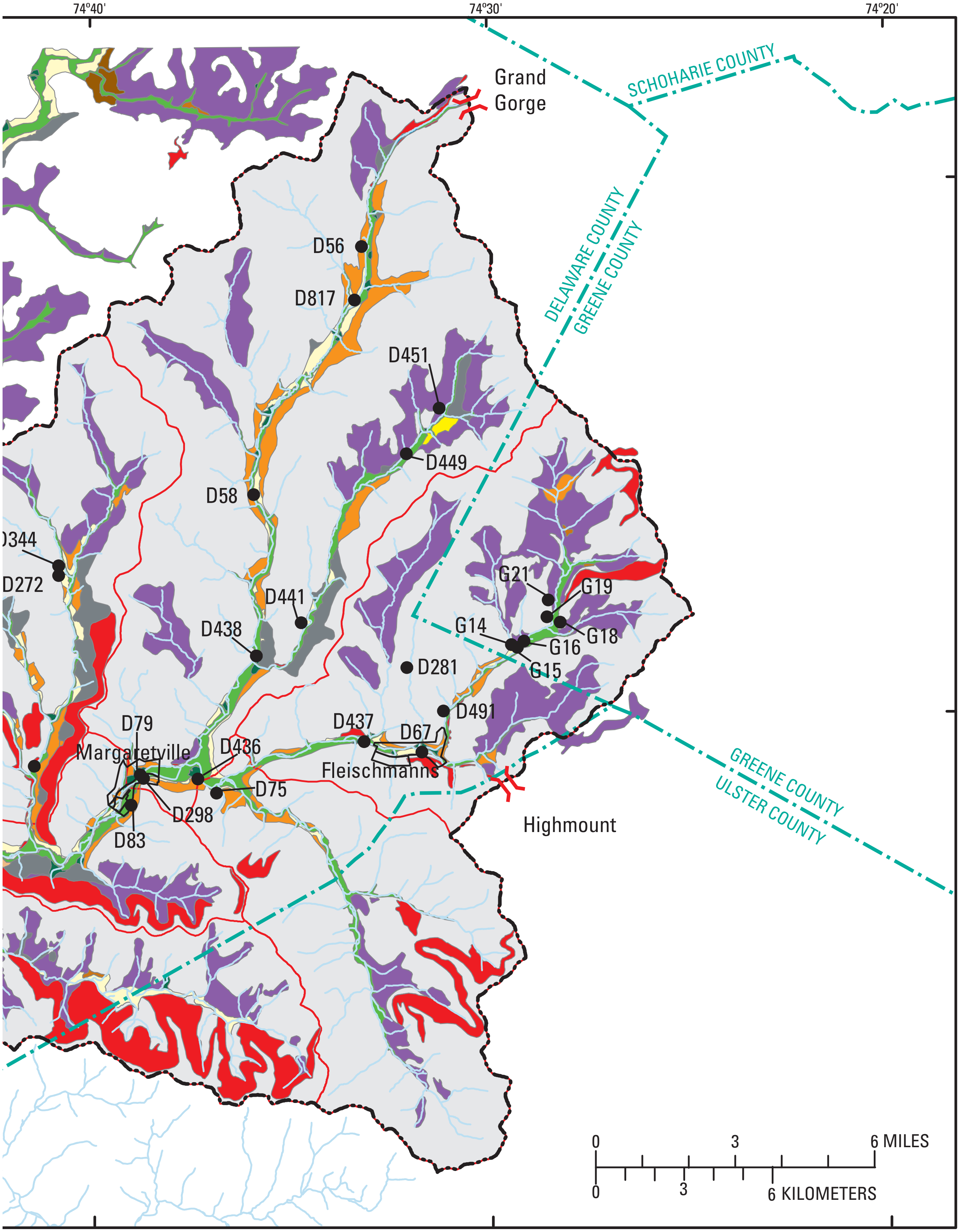
Kames are small, rounded hills that occupy the valley floor or lower hillslopes of a valley and range to 60 ft in height and 800 ft in width. Kames consist of englacial or supraglacial debris that accumulated during ice melting and typically have a wide range in grain size, sorting, and roundness. The large variability in grain size and sorting 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 and hydraulically connected to ice-contact stratified drift at depth or to adjacent or overlying saturated outwash. Surface exposures of kames, even if mostly unsaturated, can be recharge areas for saturated ice-contact deposits at depth.



Base from U.S. Geological Survey digital data, 1:100,000, 1983

Figure 2. Distribution of surficial geologic units and locations of selected wells and geologic sections within the East Branch Delaware River basin.



Geology modified by R.J. Reynolds, from Soren (1958), Kirkland (1973) Ozvath (1985), Cadwell (1999), and Natural Resources Conservation Service (1999).

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 within the valley. Kame terraces within the East Branch Delaware River Basin can have surface elevations as high as 100 ft above the valley floor and can be as much as 1,000 ft wide and up to a half-mile long. Many kame terraces have been partly eroded by postdepositional slumping or floods, especially in the upper East Branch Delaware Valley where meltwater drainage from glacial lake Grand Gorge flowed. Kame-terrace sediments within the East 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 Catskills, all of which indicate deposition in a braided glacial-stream environment.

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 Catskills—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 typically have flat-topped terrace surfaces that developed at a former lake level and consist of three units of sedimentation—topset beds, foreset beds, and bottomset beds. Topset beds are the result of the deposition of coarse sediment at or above lake level by meltwater streams. Foreset beds are the result of meltwater-stream deposition of sediment at the leading edge of a delta advancing into a proglacial lake; these deposits overlap bottomset beds, which are the result of the deposition of fine-grained sediment in deeper parts of the proglacial lake. Foreset and topset beds of kame deltas can contain considerable amounts of coarse sand and gravel, but their elevations are typically above the modern stream grade and, therefore, are largely unsaturated and generally do not represent areas of large ground-water development. They may, however, represent potential ground-water recharge areas for saturated ice-contact deposits at depth. Kame deltas are found only in the lower reaches of the East Branch Delaware River Valley, generally downstream of Margaretville, because these were the only reaches that contained glacial lakes.

Kame Moraines

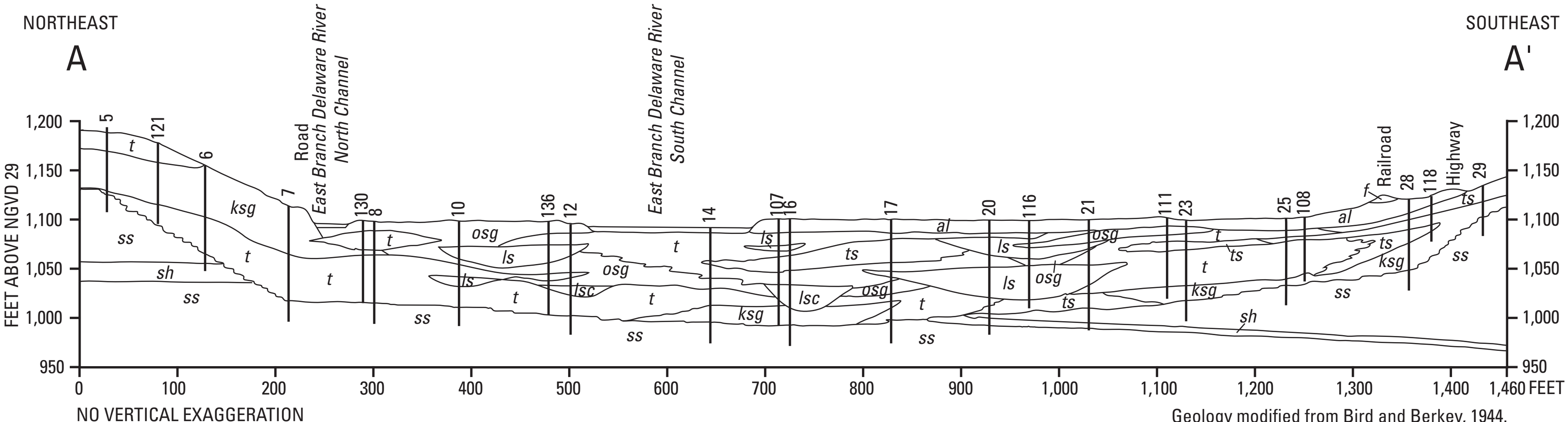
Kame moraines are ice-contact landforms that are closely associated with a temporary pause in the retreat of the ice front within a valley; they also are known as “outwash heads.” Kame moraines generally consist of extremely coarse-grained (to boulder size), well-sorted material that indicates deposition by fast-moving meltwater streams close to the ice. These deposits generally show deformation features from ice shove and can contain inclusions of till. Kame moraines indicate the location of a former ice-margin position within the valley, and their downvalley ends generally grade into outwash deposits. Kame moraines may have potential for ground-water development where they are overlapped by and buried beneath later outwash and alluvium and are mostly saturated. Kame moraines in the East Branch Delaware River Basin have been mapped near the mouths of two southward-draining tributaries — Coles Clove and Tremper Kill — and on the south wall of the East Branch Delaware River near the confluence with Mill Brook (fig. 2).

Outwash, Inwash, and Alluvium

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 East Branch Delaware River Basin, coupled 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. Sheets of outwash and alluvium in the lower East Branch Delaware River Valley (fig. 2) are generally less than 2,000 ft wide but can be as much as a half-mile wide at major valley confluences; where saturated, they form the principal stratified-drift aquifers in the basin. Outwash, or alluvium underlain by outwash, floors the main valleys tributary to the East Branch Delaware River except in their upper reaches, but these deposits rarely exceed 1,000 ft in width.

The thickness and horizontal continuity of outwash within the East Branch Delaware River Basin is highly variable as a result of the locally varying amounts of meltwater and sediment that were available within the basin. The retreat of stagnant ice, as mentioned earlier, resulted in the deposition of large amounts of ablation till in tributary valleys during early stages of deglaciation; thus, most of the valley-fill sediments within the upland tributary valleys are ablation till or a combination of ablation till, ice-contact stratified drift, and alluvial sediments. Where outwash is present in tributary valleys, it typically forms only a thin veneer over these older deposits. Outwash is as much as 100 ft thick locally within the main East Branch Delaware River Valley, however. Test borings that were made in the 1930’s for the New York City Board of Water Supply, in conjunction with the eventual construction of the Downsville dam that impounds the Pepacton Reservoir, revealed wide variability in outwash and



EXPLANATION

HOLOCENE
- *al* – Alluvium and alluvial fans
- *f* – Fill - railroad embankment fill

PLEISTOCENE
- *t* – Till - lodgement till
- *ts* – Till, sandy - ablation till and/or colluvium

PLEISTOCENE
- *osg* – Outwash sand and gravel
- *ksg* – Kame sand and gravel
- *ls* – Lacustrine sand, fine
- *lsc* – Lacustrine silt and clay

DEVONIAN
- *ss* – "Catskill Series" sandstones
- *sh* – "Catskill Series" shales

14 – Test boring, and number identifier (from Bird and Berkey, 1944)

Figure 3. Geologic section A-A′ along the Downsville dam, near Downsville, N.Y. Trace of section shown on fig.2. (Modified from Bird and Berkey, 1944)

till thicknesses. Geologic section A-A’, at the Downsville dam on the East Branch Delaware River (fig. 3), indicates that the bulk of the valley fill here consists of till, outwash, possibly some ice-contact sand and gravel, colluvium, but little lacustrine material. Slightly further upstream, near Shavertown, a series of test borings drilled for the construction of a bridge (Section B-B’, fig. 4) over the Pepacton Reservoir reveal about 80 ft of till on the south side of the valley; this till thins to about 20 ft in the valley center and is overlain by 10-15 ft of alluvium. The saturated thickness of the alluvium at this locality is only about 10 ft. No lacustrine sediments are indicated in well logs at this site.

Alluvium

Alluvium consists primarily of fluvially deposited sediment ranging in size from silt to fine to coarse sand and fine gravel, generally less than 6 ft in thickness, that occurs 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 typically overlies outwash on valley floors.

Inwash

Inwash deposits are stratified accumulations of sand and gravel deposited in main 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. Deposits of inwash are found in the upper reaches of the Batavia Kill tributary to the East Branch Delaware River. The permeability of inwash is generally high, like that of outwash, but is highly variable.

Bedrock Geology

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

Stratigraphy

The entire Catskill region, including the East Branch Delaware River Basin, is underlain by the Catskill Mountain Series (of Mather, 1840; Chadwick, 1936) of Upper Devonian age, which is as much as 6,000 ft thick and consists of marine and nonmarine red and gray sandstones, shales, and conglomerates. Beds within the formation are nearly flat lying and dip gently to the southeast and northwest as a result of broad folds whose axes trend northeastward (Soren, 1963). The Catskill Mountains were formed by the dissection of a bedrock plateau, by streams, and by glacial erosion. The highest hilltops and ridges, which form the principal drainage divides, are underlain by various beds of siliceous conglomerates 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, 1961, 1963).

Fisher and others (1970) and Rickard (1975) divided the Catskill Mountain Series (or Catskill Facies, which pertains to the nonmarine red and gray sandstones and shales) in the East Branch Delaware River Basin into five major formations— the Honesdale, Slide Mountain, and Upper Walton Formations of the West Falls Group, the Lower Walton Formation of the Sonyea Group, and the Oneonta Formation of the Genesee Group (Rickard, 1975, pl. 3). The stratigraphically higher (and younger) Honesdale and Slide Mountain Formations occupy the ridgetops of the southern escarpment, which forms the drainage divide between the East Branch Delaware River Basin and the Beaver Kill basin to the south. The Upper Walton Formation generally occupies the uplands within the East Branch Delaware River Basin and its ridges form the drainage divides between the seven main tributaries to the East Branch Delaware River. The Lower Walton Formation underlies the lower slopes and valleys of the main tributaries, whereas the Oneonta Formation underlies the upper East Branch Delaware River from Grand Gorge south to Stratton Falls (Fisher and others, 1970). The areal distribution of these major bedrock formations within the East Branch Delaware River basin is illustrated in figure 5.

Three intersecting fracture planes, one of which is parallel to the bedding and two of which are vertical, appear in most of the beds of the Catskill Mountain Series. The two vertical fracture sets are roughly perpendicular—one striking northeast, from N15° to N35°E, and the other striking northwest, from N25° to N80°W (Perlmutter, N.M., and Salvas, E.H., 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 (Parker and others, 1964; Soren, 1963). The fracture sets also serve to increase the permeability of the rock and are the reason for the relatively high yield of bedrock wells in this region. 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 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).

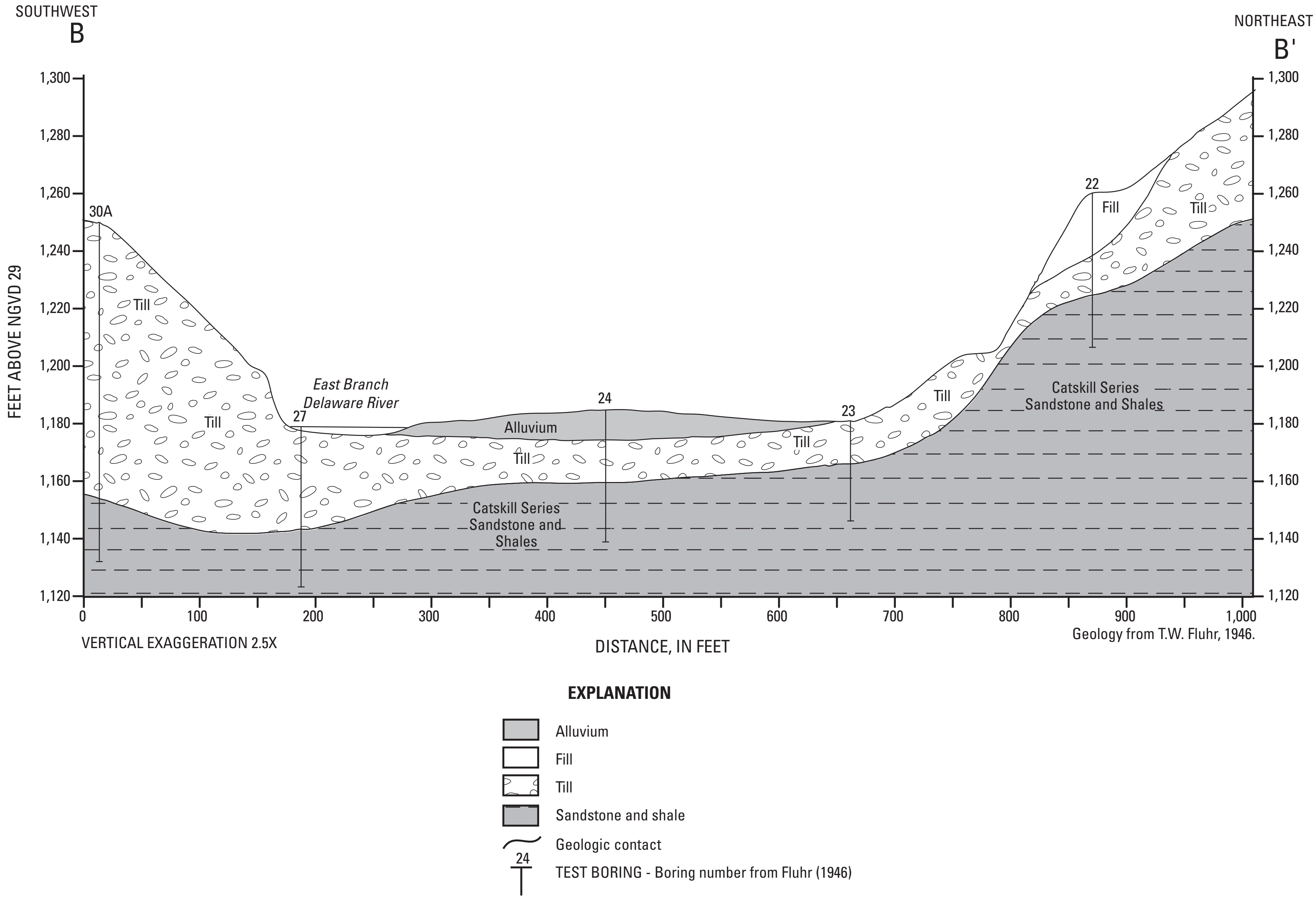


Figure 4. Geologic section B-B′ along the Shavertown Bridge, at Shavertown, NY. Trace of section shown on fig. 2. (From Fluhr, 1946)

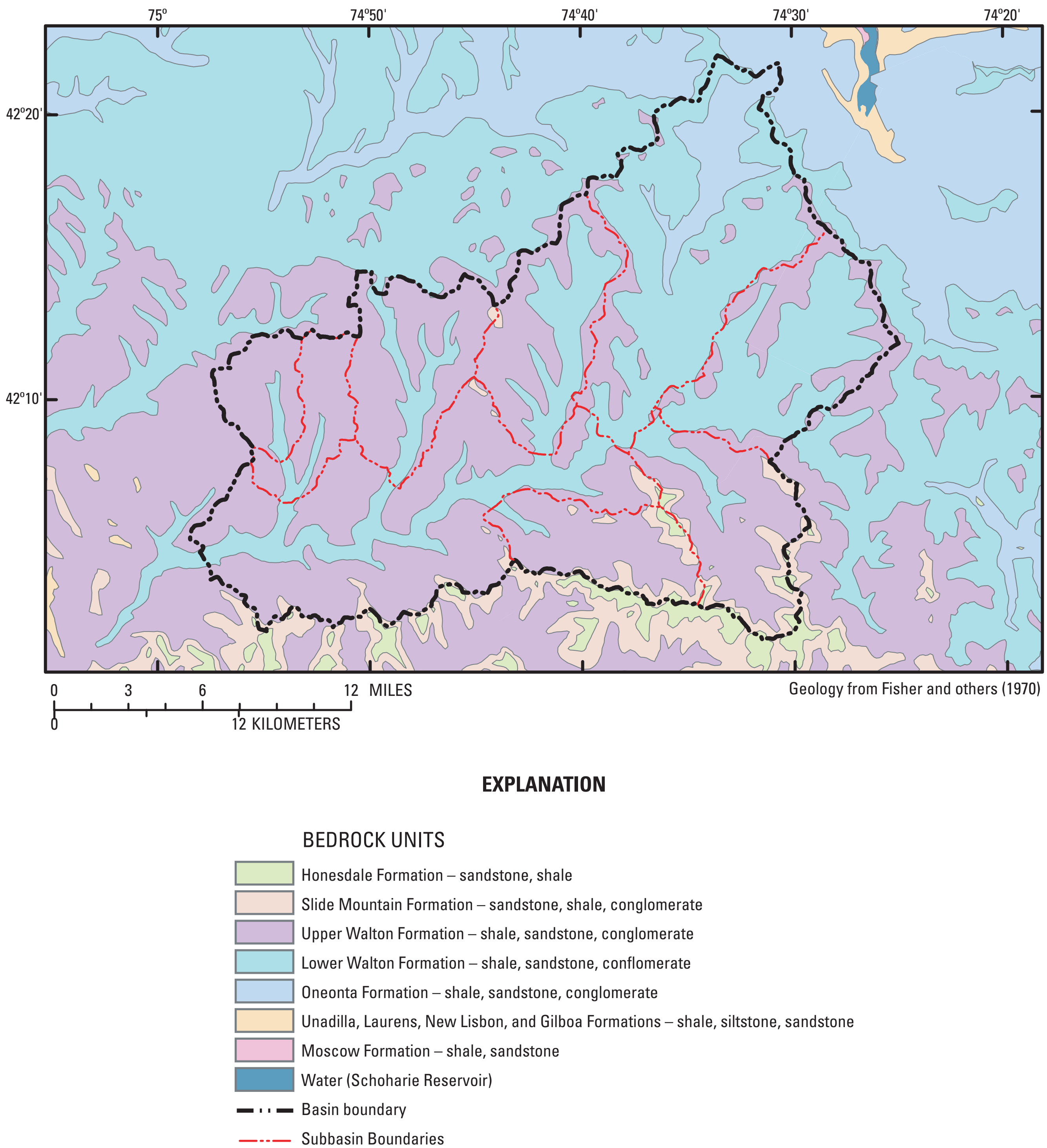


Figure 5 Distribution of major bedrock units within the East Branch Delaware River basin in southeastern New York.

Stress Relief and Fracturing

Stress relief of sedimentary rocks in valleys has been shown to be the principal factor in enhancing the secondary permeability of clastic 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 compressional (upward) forces on the bedrock that directly underlies the valley floor. These forces typically produce vertical tensile fractures in bedrock on the valley walls and vertical fracturing, low-angle faulting, and arching of beds

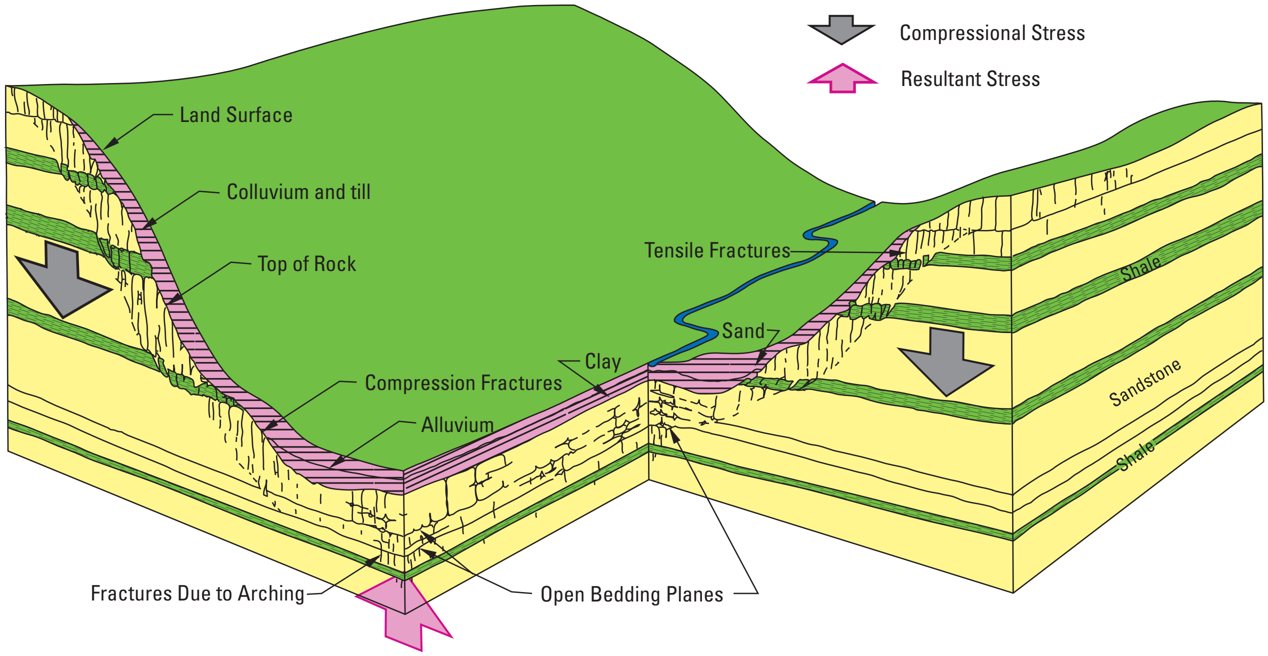


Figure 6. Generalized geologic section showing features of stress-relief fracturing (from Wyrick and Borchers, 1981, fig.3.2-2).

beneath the valley floor. The tensile fractures on the valley walls can result in blocky or steep cliffs with near-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. Soren (1963) reports anticlinal crests in the East and West branches of the Delaware River near the Pepacton Reservoir, and Heisig (1999) depicts stratigraphy (based on natural gamma radiation logs) in the Batavia Kill valley near Windham, N.Y. (in the adjacent Schoharie Creek Basin to the east), that appears to show arching of beds (or an anticlinal structure) beneath the thalweg of the bedrock valley there. Therefore, a similar anticlinal bed structure and its associated vertical fracturing can be reasonably assumed to be present beneath the main East Branch Delaware River Valley and many of its larger tributaries. Valley-bottom and valley-side fracturing because of 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 6.

Well Yields

Records of 199 wells drilled into the Catskill Mountain Series within Delaware County (Soren, 1963) indicate well depths ranging from 18 to 687 ft, with a median depth of 158 ft; most well depths range from 100 to 300 ft. Yields range from 0 to 450 gal/min, with a median yield of about 15 gal/min (Soren, 1963). Specific capacities range from less than 0.2 to 4 gal/min per foot of drawdown (Perlmutter, N.M., and Salvas, E.H., U.S. Geological Survey, written commun., 1957). The maximum known yield from a bedrock well in the East Branch Delaware River basin (450 gal/min) is from well D-56, an 8-in diameter well that is 404 ft deep and is completed in the Oneonta Formation, which underlies the northern part of the East Branch Delaware River valley. Similarly, the maximum known yield from a bedrock well within Delaware County is from well D-15, a 12-in. industrial well completed in sandstone and shale near Sidney, N.Y. (within the Susquehanna River Basin) and yielding 550 gal/min. 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 1930's and 1940's along the routes of the nearby East and West Delaware Aqueducts indicate artesian flow at several borings in valley floor and lower hillside settings because the potentiometric surface was more than 10 ft above land surface.

Saline Ground Water

Ground water 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 to 0.17 mg/L), but can be elevated locally (Parker and others, 1964).

Saline ground water, however, has been reported at depth within the East Branch Delaware River Basin and within the

Schoharie Creek Basin to the east. Soren (1963) reported two bedrock wells, with depths of 140 and 420 ft, which produced water with elevated chloride concentrations. Water from well D-59 at Grand Gorge (140 ft deep, fig. 2) had a chloride concentration of 170 mg/L when it was sampled in 1946, and a sample from D-102 at Walton (420 ft deep) initially had a chloride concentration of 800 mg/L in 1946, but had a reduced chloride concentration of 126 mg/L when it was resampled in 1957. Perlmutter and Salvas (Perlmutter, N.M. and Salvas, E.H., U.S. Geological Survey, written commun., 1957) reported a 462-ft-deep bedrock well in central Sullivan County that produced natural gas (methane) and saline water from a gray shale unit, and a 208-ft-deep well at Deposit, N.Y. (D-114), in the West Branch Delaware River Basin, that produced water with a chloride concentration of 310 mg/L. All of these wells probably intersect marine shales of the Catskill Series and tap naturally occurring brine (connate water). Salty ground water has also been reported in deep wells completed in Catskill Series rocks within the adjacent Schoharie Creek Basin to the east. Heisig (1999) reported three bedrock wells within the Batavia Kill valley near Windham, N.Y. that produce very saline ground water 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 ground water entering the boreholes from fractures ranged from 370 to 13,000 mg/L (Heisig, 1999, appendix B). Not all deep bedrock wells that intercept saline water at depth produce impotable water, however, 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 up on the valley walls or on hilltops are generally in areas of ground-water 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 ground-water discharge, where the vertical gradient and, thus, the flow within the well bore, are upward. Therefore most bedrock wells located on valley floors, and that intercept saline ground water at depth, usually yield water that becomes impotable through the upward movement of saline water within the well bore.

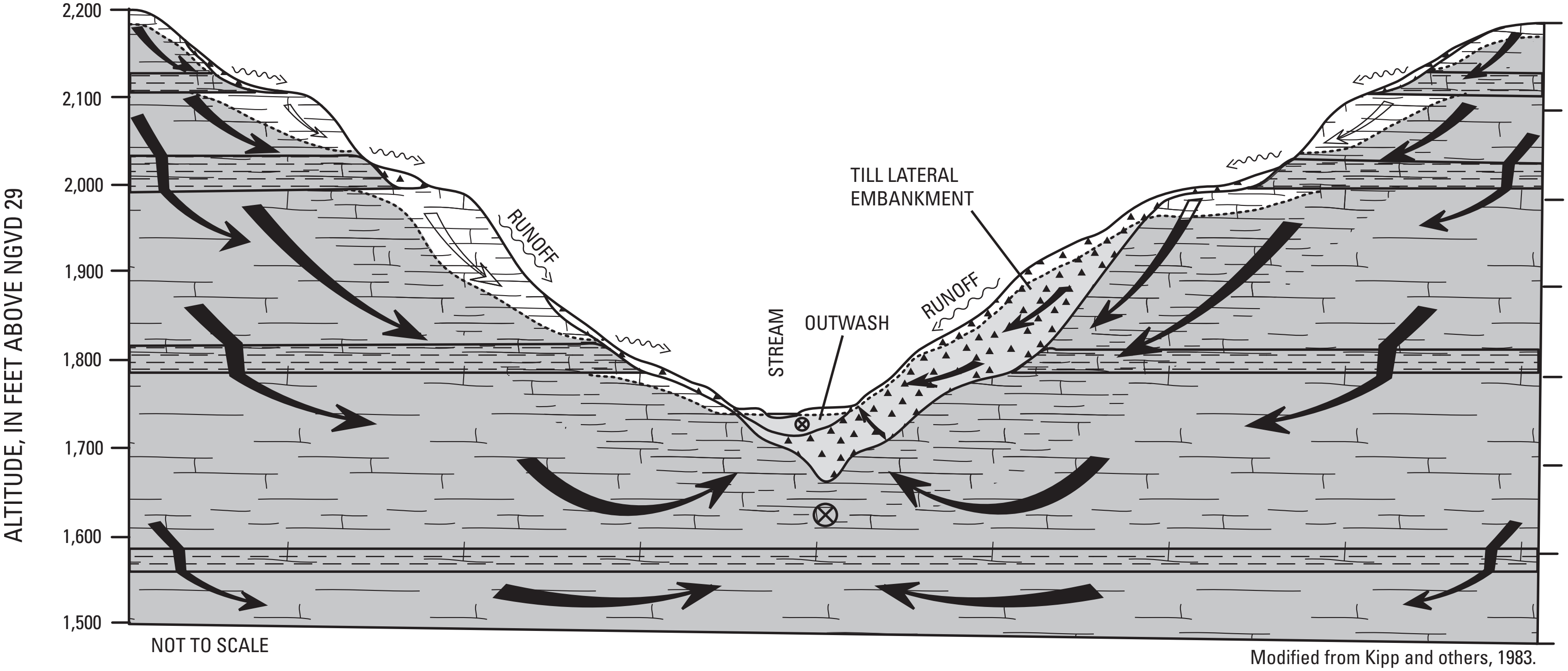
Ground-Water Flow System

The sequence of permeable sandstone units alternating with less permeable shale units within the Catskill Mountain Series (of Mather, 1840) forms a series of stacked aquifers separated by confining units of varying, but generally lesser thickness, than that of 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 ground water 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 7. 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, ground water 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 only during 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 where they extend into the core of the mountain, but here they are less fractured or jointed, and ground water within these units moves mainly as slow, diffuse flow through small intergranular spaces and small, discontinuous fractures and, therefore, probably contribute little to contact springs.

Ground water within saturated sandstone that is overlain by thick deposits of ablation till (lateral embankments), is generally confined, with ground water levels typically 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 proposed route of the East Branch Delaware aqueduct crossing of Beaver Kill at Lewbeach, in adjacent Sullivan County, indicate that artesian flow from a 3-in-diameter casing ranged to 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 explain the relatively high base flows of streams in this basin.

Springs

Springs are a major source of domestic ground-water supplies for much of the population of the East Branch Delaware River Basin, and much of the Catskill Mountain region. Well and spring inventories were conducted by the USGS during previous ground-water investigations of Delaware County (Soren, 1963) and of the Delaware River Basin in New York (Perlmutter, N.M., and Salvas, E.H., 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 Unit,” which includes the West and East Branch Delaware Basins and most of adjoining Sullivan County. Nearly all of these springs were situated on hillsides, and originated from bedding-plane openings or other fractures at rates as high as 106 gal/min, although most discharged only 2 to 3 gal/min (Perlmutter, N.M., and Salvas, E.H., U.S. Geological Survey, written commun., 1957). Similarly, Soren (1963) published



EXPLANATION

SANDSTONE – fractured, saturated where shaded. Forms a regional, confined aquifer in the Catskill Mountain region

SHALE – Forms confining beds within bedrock aquifer

TILL – lateral embankment of ablation till; saturated where shaded

OUTWASH – valley train outwash and alluvium; saturated where shaded. Forms main water table aquifer in valleys.

WATER TABLE

SPRING DISCHARGE – contact springs at the base of sandstone units

GROUND-WATER FLOW – generalized direction of ground-water flow within zone of saturation

UNSATURATED FLOW – generalized direction of unsaturated flow in fractured bedrock

DOWNVALLEY FLOW – indicated flow into the page (downvalley)

Figure 7. Conceptual diagram of York (from Reynolds, 2000, fig.8)

records of 184 representative springs in Delaware County, nearly all of which 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. The average yield for these 178 springs, which includes 11 public water supplies, was 8.5 gal/min, with a median yield of 3 gal/min. Most domestic springs in Delaware County have yields ranging from 3 to 5 gal/min (Soren, 1963). Records of these 178 springs show that they range in altitude from 1,000 ft to 2,360 ft above NGVD 29, with a mean altitude of 1,676 ft. A plot of yield as a function of altitude for these 178 springs (fig. 8) indicates that most of the yields are less than 10 gal/min, and that most of the springs are at altitudes between 1,400 and 2,000 ft above NGVD 29.

Many small villages within the East 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 are 15 small municipalities in Delaware County that obtain all or part of their water needs from springs. The prolific use of springs for domestic and municipal water supplies in the Catskill Mountain region indicates a lesser dependence on drilled wells for drinking water than in other parts of New York. The spatial distribution of well records in the USGS National Water Information System (NWIS) database for the East Branch Delaware River basin appears to support this conclusion, in that the majority of the drilled wells are on the valley floor, with relatively few wells drilled into bedrock in the uplands. The abundance of springs issuing from Catskill Mountain Series sandstones (Soren, 1963) reflects the relatively high secondary permeability of these rocks because of the presence of both vertical and bedding-plane fracture sets. The abundance of springs also has a pronounced effect on the base flow of tributary streams within the East Branch Delaware Basin (as discussed later), as many of the small tributaries originate as spring discharge from hillsides (Perlmutter, N.M., and Salvas, E.H., U.S. Geological Survey, written commun., 1957).

Stratified-Drift Aquifers

The locations of stratified-drift aquifers in the East Branch Delaware River Basin are directly related to the distribution of outwash and ice-contact deposits within each subbasin. In general, the sediments in the tributary valleys become less stratified and sorted as the valley size decreases. Most of the small tributary valleys contain little stratified drift, and whatever is present consists of poorly sorted ice-contact material (Ozvath and Coates, 1986). The valleys of the upper East Branch Delaware, Tremper Kill, Platte Kill, Bush Kill, and Dry Brook (fig. 2), however, contain 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 distribution and characteristics of aquifers in each of these valleys is discussed in the following sections.

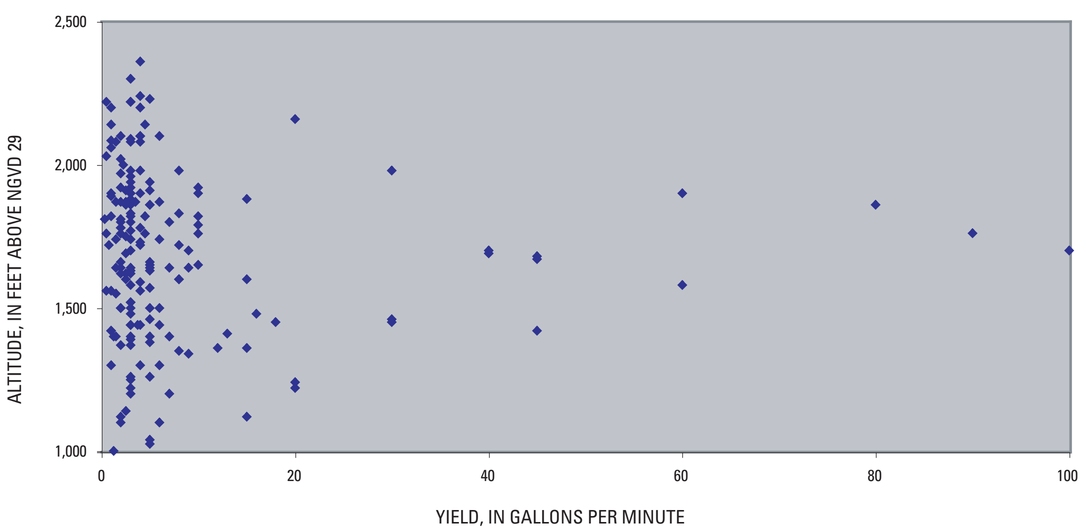


Figure 8 Yield of 178 springs in Delaware County, N.Y., as a function of altitude (Data from Soren, 1963).

Upper East Branch Delaware subbasin

The upper East Branch Delaware subbasin encompasses about 81 mi^2, and contains large deposits of outwash and ice-contact sand and gravel. This subbasin represents the East Branch Delaware River Basin upstream from Margaretville, including its main tributary, the Batavia Kill. Till comprises the largest surficial unit in this subbasin and covers 89.4 percent (72.4 mi^2) of the subbasin. The headwater valleys in this subbasin contain several large areas of thick ablation till that occupy 10.7 percent (8.68 mi^2) of the subbasin. Most of the East Branch Delaware River valley above Halcottsville is flanked with large kame-terrace deposits, which were deposited against and atop stagnant glacial ice by large flows of meltwater. Ice-contact deposits cover about 4.4 percent (3.54 mi^2) of the subbasin area. The main stratified-drift aquifer in this valley consists of outwash and alluvium which occupies the valley floor and represent 5.5 percent (4.47 mi^2) of the subbasin area. All of the stratified drift units combined account for 10 percent (8.16 mi^2) of the subbasin area. Several communities obtain municipal ground-water supplies from the outwash aquifer, including the Roxbury Water District (pop. 750), the hamlet of Hallcottsville (pop. 43), and the Grand Gorge Water District (pop. 380) (New York State Department of Health, written commun., 2000). Only a limited amount of well data in this valley is available to define the thickness and hydraulic properties of the aquifer because of the sparse population, but several well records in the USGS database provide some information on the range in thickness of the outwash aquifer. Well records appear to indicate that the outwash aquifer ranges up to almost 90 ft in thickness locally, and averages about 50 ft thick. Well D-58, a domestic well about 2 mi north of Hallcottsville is 86 ft deep, is completed open-ended in sand and gravel, and yields about 35 gal/min. Well D-438, at Kelly Corners near the confluence of the upper East Branch Delaware and the Batavia Kill, is 54 ft deep, is also finished open-ended, and produces 12 gal/min. Drillers logs for both wells record the material penetrated as “sand and gravel.” Further north, in the village of Roxbury, the Town of Roxbury uses two supply wells that are completed in outwash sand and gravel and have been pumped at 350 and 207 gal/min, respectively, during tests. A newly installed supply well for the Town of Roxbury (D-817) is 70 ft deep and is completed with 15 ft of stainless-steel well screen. This well has yielded 350 gal/min with a specific capacity of 26.6 (gal/min)/ft of drawdown in a 72-hour aquifer test. A second well is 36 ft deep and is equipped with a 10-ft screen, and has yielded 207 gal/min with a specific capacity of 51.9 (gal/min)/ft of drawdown (GeoLogic NY, unpublished report, 2001). A nearby well drilled to bedrock in Roxbury indicates that the sand and gravel aquifer here is from 80 to 85 ft thick and is underlain by till. Drillers’ logs indicate that the sand and gravel aquifer here contains many cobbles and boulders, and is very silty, as is common in areas where glacial ice has melted in place. Well records from the adjacent Batavia Kill valley indicate that the sand and gravel ranges from 60 to 80 ft thick in the northern part of the basin (wells D-449, D-451) to about 20 ft thick near its confluence with the upper East Branch Delaware River Valley (D-441). Yields of two domestic wells completed open ended in the sand and gravel aquifer in the adjacent Batavia Kill valley range from 12 to 30 gal/min. Drillers’ logs for the few well records in this valley seem to indicate that the upper reach of the valley, northward of the Roxbury Town line, contains mostly sand and gravel, and that the narrower, southernmost reach contains ablation till (“hardpan”) and sand and gravel.

Tremper Kill subbasin

The Tremper Kill subbasin encompasses approximately 33 mi^2 and also contains appreciable deposits of ice-contact sand and gravel and outwash. Till is the most extensive mapping unit in this subbasin; all till units, including colluvium, total 92.4 percent of the basin (30.5 mi^2), but upland valleys filled with thick deposits of lodgment till account for about 27.2 percent (9 mi^2) of the subbasin area. Stratified-drift units, including alluvium, outwash, and ice-contact deposits, account for 7.2 percent (2.36 mi^2) of the subbasin area. Drillhole data from the Tremper Kill subbasin are sparse, and represent only a few well records near the village of Andes; however, these data indicate that the thickness of valley fill near Andes is around 80 ft. Well D-87, at Andes, was drilled though 78 ft of till into bedrock. Wells D-168 and D-76, also at Andes, were completed in the outwash aquifer here for a dairy-processing facility; they are 32 and 21 ft deep and produce 55 and 130 gal/min., respectively; the latter with only 4 ft of drawdown, and a specific capacity of 32.5 (gal/min)/ft of drawdown. Some well logs illustrate the thickness of lodgment till in some of the upland basins. Well D-423, just north of the divide between the Tremper Kill subbasin and the West Branch Delaware River Basin, penetrated 184 ft of till overlying bedrock.

Platte Kill Subbasin

The Platte Kill subbasin comprises approximately 34.9 mi^2, and contains appreciable ice-contact deposits, as well as outwash. Stratified drift (alluvium, outwash, and ice-contact deposits) accounts for about 7 percent (2.45 mi^2) of the subbasin area, and till (including areas of thin till and exposed rock) accounts for 93 percent (32.45 mi^2). Thick till deposits in the headwater valleys of the Platte Kill are one of the largest single mapping units and cover about 8.2 percent (2.85 mi^2) of the subbasin. Exposed bedrock, another large mapping unit, comprises 7.5 percent (2.61 mi^2) of the subbasin area, and is seen primarily on the steep, eastern valley wall of the Platte Kill. Well data are sparse, as in the other subbasins, but records from a few wells can provide some information on the thickness of the valley fill along this tributary. Data from several wells at New Kingston, where three upland tributary valleys meet, indicate that the thickness of the stratified-drift aquifer there ranges from 50 to 60 ft. Well D-272, drilled for a dairy-processing facility at New Kingston, is 4 in. in diameter, 40 ft deep, equipped with 4 ft of screen, and yields 120 gal/min. Drillers' logs of two nearby bedrock wells (D-509 and D-344), which intercept bedrock at 50 ft and 61 ft, respectively, report only sand and gravel overlying bedrock. The only indication of the aquifer thickness further south is from well D-268, a 24-ft deep driven well about 2 mi north of Dunraven. Most of the smaller tributary valleys contain largely till, but some contain narrow stratified-drift sand-and-gravel aquifers. An example is seen in the western end of the Bryant's Brook tributary valley, also mapped as Palmer Hollow, where well D-396 is completed open-ended in 65 ft of gravel with a reported yield of 30 gal/min.

Bush Kill subbasin

The Bush Kill subbasin encompasses about 46.7 mi^2, and is characterized by large upland bodies of thick till, and a well-developed valley train of outwash overlain by alluvium. Stratified-drift deposits occupy about 5 percent (2.3 mi^2) of the subbasin, and till covers the other 95 percent (44.38 mi^2). Upland valleys filled with thick deposits of lodgment till represent 22 percent (10.45 mi^2) of the subbasin, whereas alluvium and outwash account for about 3 percent (1.5 mi^2). Scattered well data from throughout the Bush Kill subbasin and its tributaries provide some information on the relative thickness of the valley fill aquifer. At the mouth of the Bush Kill subbasin, near Arkville, the valley merges with the Dry Brook valley just upstream from the East Branch Delaware River Valley, where the valley width reaches a half-mile in places. Well logs from the supply wells of the Arkville Water District indicate that the outwash aquifer here is at least 60 ft thick in the valley center. The log of well D-436, at Arkville, indicates an upper unit of alluvium and outwash that is 20 ft thick, underlain by 30 ft of lacustrine fine sand ("quicksand") that overlies 10 ft of gravel. The presence of lacustrine sediment here indicates that a local, temporary proglacial lake formed here and lasted long enough for 30 ft of fine-grained sediment to be deposited. The depth to bedrock decreases further up the narrow Bush Kill valley and the outwash aquifer becomes thinner. The log of well D-437 at Covesville, just west of Fleischmanns, indicates bedrock at 28 ft, overlain by sand and gravel. Further east, at Fleischmanns, the valley narrows considerably and the aquifer thins. Well D-67, a 150-gal/min supply well for the Village of Fleischmanns, is located just east of the village, and intercepts bedrock at 16 ft. Further upstream, into the Vly Creek valley, the log of well D-491 indicates that the depth to bedrock is about 25 ft. The Vly Creek valley widens further upvalley near Halcott Center in Greene County, however, and well records (G-830, G-15, and G-16) indicate depths to bedrock ranging from 60 to 90 ft in the valley center. Drillers' logs here typically report the material penetrated as "boulders, hardpan, and gravel"; an indication of the increasing amount of lodgment till present in these headwater valleys. Records from three wells about a mile further up the Vly Creek valley report depths to bedrock ranging from 55 to 95 ft (wells G-19, G-21) and indicate from 40 to 60 ft of till and colluvium (hardpan) overlying ice-contact sand and gravel (wells G-18, G-21), which represent locally confined aquifers. Most of the other smaller tributaries in the upper reaches of the subbasin contain thick deposits of lodgment till. For example, well D-281, in the Little Red Kill valley, 2 mi north of the village of Fleischmanns, penetrates 110 ft of till overlying bedrock.

Dry Brook subbasin

The Dry Brook subbasin, or that part of the larger Dry Brook basin that is gaged along with the Bush Kill subbasin, comprises about 35.4 mi^2. This subbasin contains prominent kame terraces near the confluence of Dry Brook with the Bush Kill, and the valley is floored along most of its length by alluvium and outwash. Stratified drift occupies about 5 percent (1.74 mi^2) of the subbasin area, whereas till covers the remaining 95 percent (33.74 mi^2). Upland hollows filled with thick lodgment till account for 4.5 percent (1.6 mi^2) of the subbasin area, and exposed or thinly covered bedrock accounts for 6.2 percent (2.2 mi^2). Well data from the Dry Creek valley are sparse and give little indication of the thickness of the outwash aquifer, except for well D-75, which was drilled on the valley flat near the mouth of the Dry Brook valley and intercepts bedrock at 50 ft. Field notes and mapping by Soren (Soren, Julian, U.S. Geological Survey, unpublished field maps, 1955) indicate that the entire length of the Dry Brook valley is floored with sand and gravel and that, in some places, alluvial or outwash terraces overlie bedrock on both banks of the stream. The stream, in other areas, notably just upstream from the Ulster County boundary near the confluence with Rider Hollow, runs directly on bedrock. This suggests that the outwash aquifer throughout most of the length of Dry Brook is extremely thin and probably does not exceed 30 ft in thickness anywhere.

East Branch Delaware River Valley

Well data from several wells in the main East Branch Delaware River valley near Margaretville show that the average thickness of the valley fill aquifer here is around 50 ft. Well D-79, a 6-in.-diameter supply well for a dairy-processing facility, is in the valley center across from the "nose" of Pakatakan Mountain. This well is 45 ft deep, is screened in sand and gravel, and yields 240 gal/min. Nearby, well D-298, a supply well for the village of Margaretville, is 35 ft deep and is also screened in sand and gravel. The greatest reported thickness of stratified drift is at well D-83, located on a kame terrace on the west side of Pakatakan Mountain. This well penetrated 140 ft of stratified drift before reaching bedrock, and its location atop a kame terrace that is 60 ft above the valley floor indicates that the depth to bedrock beneath the valley floor here is about 80 ft.

Base Flow and Ground-Water Recharge

The East Branch Delaware River Basin contains eight subbasins in which streamflow is gaged, or has been gaged in the past, by the USGS. Some of these gaging stations have periods of record as long as 65 years, whereas others are relatively new (less than 5 years old), and still others have been discontinued. The construction of two new stream-gaging stations in 1996-97 — Bush Kill near Arkville, N.Y. and Dry Brook at Arkville, N.Y. — permits a comparison of streamflow statistics from six currently gaged subbasins and of one ungaged subbasin (by subtraction of flow of at one station from that at another). Four of these stations have long periods of record (greater than 65 years), but a comparison of streamflow statistics among them requires a common period of record (1998-2001), as dictated by the short period of record (less than 5 years) of the two newest stations. Records from two discontinued gages at the western end of the basin — Terry Clove Kill near Pepacton, N.Y. and Coles Clove Kill near Pepacton, N.Y. — allow a comparison of flow at these two stations for the period 1945-52.

Base-flow and Recharge Analysis

For this analysis, daily mean stream discharge values for the six eastern gaged subbasins were retrieved from the USGS database for the 4-year period beginning January 1998 and ending December 2001. Daily mean values of streamflow for a seventh subbasin, herein called the upper East Branch Delaware River, were computed as the daily mean flow for the East Branch Delaware River at Margaretville, N.Y. minus the daily mean flow for Dry Brook at Arkville, N.Y. In addition, daily mean discharge for the two discontinued western stations — Terry Clove Kill and Coles Clove Kill — were retrieved for the period January 1945 through December 1952. A data file for each of these nine stations was constructed for subsequent use in analytical programs developed by Rutledge (1993, 1998, 2000). Stations used in this study are listed in table 2; station locations are shown in figure 9.

The data files of daily mean flow for these nine stations were applied to three computer programs developed by Rutledge (1993, 1998, 2000) to: (1) partition the streamflow hydrograph for each station into baseflow and runoff components, and (2) estimate the amount of ground-water recharge that occurred in each subbasin for the period of record analyzed. These three computer programs, called RECESS, PART, and RORA, are described below.

Table 2. Recession-analysis and master recession-curve data for eight subbasins (nine gaging stations) in the East Branch Delaware River Basin in southeastern New York

[mi^2, square miles; MRC, master recession curve; min log Q; minimum value of logarithm of stream discharge; max log Q, maximum value of logarthm of stream discharge. Locations are shown in fig. 1. n/a, no record]

Station name	Station Number	Drainage area (mi^2)	Period of record	Period analyzed (month/year)	Number of recession segments used	Median recession index (days per log cycle)	Range of MRC	
							Min. log Q	Max log Q
Bush Kill near Arkville	01413398	46.	10/97 - present	1/1998 - 12/2001	8	56.3	1.509	2.048
Dry Brook at Arkville	01413408	82.	12/96 - present	1/1998 - 12/2001	15	65.6	1.197	2.232
East Branch Delaware River at Margaretville	01413500	163.0	02/37 - present	1/1998 - 12/2001	11	55.1	1.507	2.526
Upper East Branch Delaware Ruver	*	80.8	n/a	1/1998 - 12/2001	12	57.8	1.010	2.177
Platte Kill at Dunraven	01414000	34.	10/41 - 09/62 12/96 - present	1/1998 - 12/2001	6	42.8	.578	1.720
Mill Brook at Dunraven	01414500	25.	02/37 - present	1/1998 - 12/2001	14	61.9	.827	1.937
Tremper Kill near Andes	01415000	33.	02/37 - present	1/1998 - 12/2001	8	59.1	.928	1.771
Terry Clove Kill near Pepacton	01415500	13.6	1937 - 62	1/1945 - 12/1952	10	40.8	.506	1.698
Coles Clove Kill near Pepacton	01416500	28.0	1945-53	1/1945 - 12/1952	15	31.3	.509	1.818

* Mean daily discharge values for this subbasin were calculated by subtracting the flow of station 01413408 (Dry Brook at Arkville, N.Y.) from station 01413500 (East Branch Delaware River at Margaretville, N.Y.)

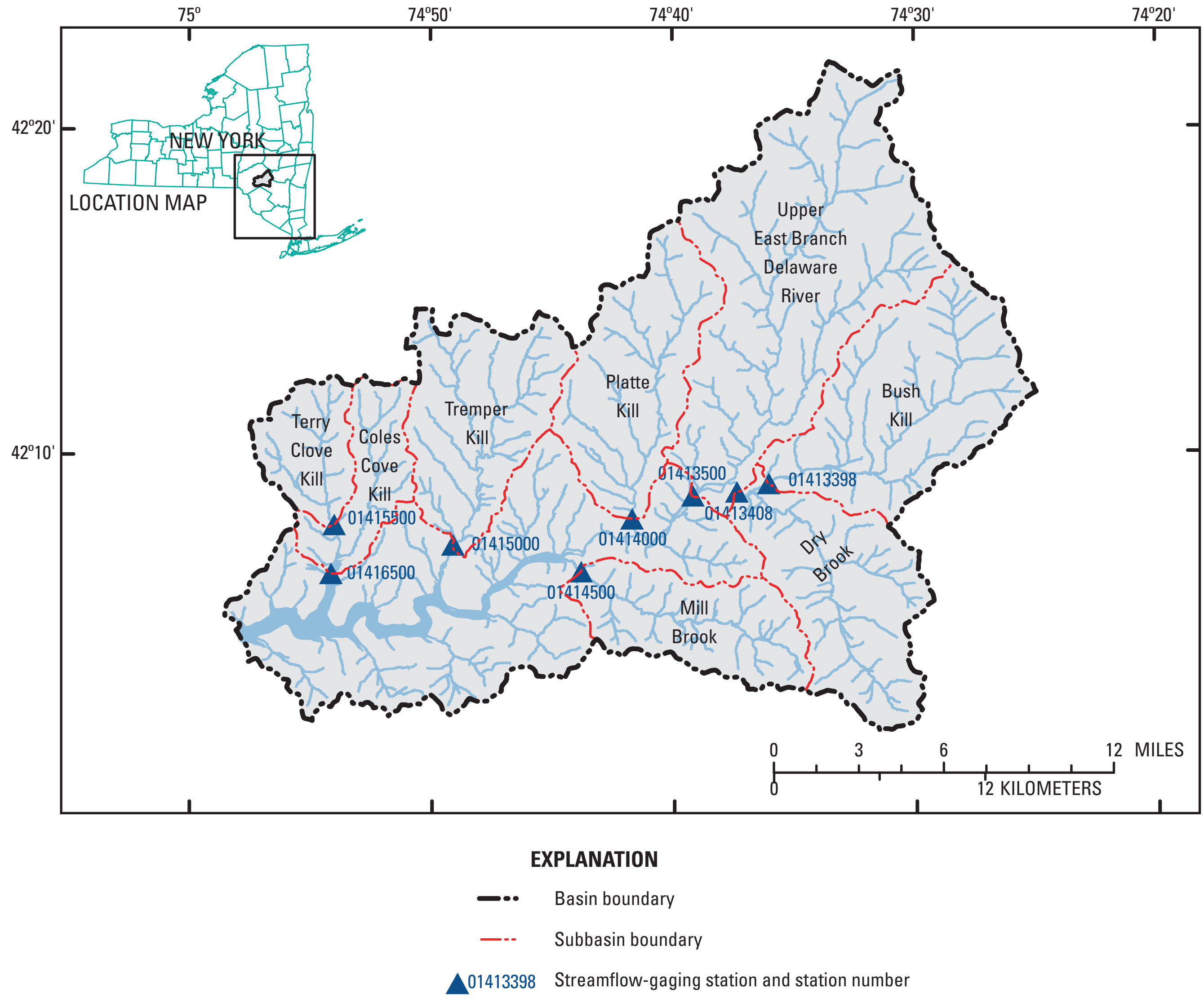


Figure 9 Locations of stream gaging stations in the East Branch Delaware River Basin in Southeastern New York.

Program RECESS

The RECESS program works interactively with the user to: (1) select segments of ground-water recession from a station hydrograph of daily mean values, and (2) develop a master recession curve (MRC), which describes the recession of streamflow under base-flow conditions. In this context, base flow conditions exist when all streamflow is derived from ground-water discharge to the stream, recharge from previous precipitation has ceased, and the profile of ground-water head distribution from the divide to the stream is nearly stable. In use, the program reads a user-constructed file of daily mean discharge values and identifies all streamflow-recession segments that exceed some specified length of time during a specified period of interest. The user then selects segments of these recessions that appear as straight lines on a semilog plot; these segments represent ground-water discharge, or base flow. The program determines, for each selected segment, the best linear equation that best relates time, in days, to the logarithm of streamflow, then extracts from this equation a recession index (K) for the segment expressed in days per log cycle. The user repeats this procedure interactively for all recessions of a specified minimum length (usually 10 days) and for a specified season (usually the nongrowing season) for the period of record to be analyzed. Next, the previously calculated values of K are used in the program as data points to define the best linear equation for K as a function of the logarithm of flow. Coefficients of this equation are then used to construct the master recession curve (MRC), which is a second-order polynomial expression for time as a function of the logarithm of flow (Rutledge, 1998). The MRC is subsequently used in the program RORA, described later, to quantify ground-water recharge for the basin being studied for a given period.

Program PART

The program PART estimates the base-flow component of a streamflow hydrograph through a partitioning (hydrograph-separation) procedure. The program uses the daily mean discharge values dataset that has been previously constructed by the user, and applies a linear interpolation method to estimate the base-flow component under each hydrograph peak (the base-flow contribution during periods of runoff). This method differs from other published automated partitioning methods in that it is based on antecedent streamflow, whereas other methods are based on antecedent precipitation (Rutledge, 1998). During execution, the program creates a one-dimensional array of daily streamflow values, then searches the array for days that fit an antecedent recession requirement. On each of these days, ground-water discharge is designated as being equal to streamflow as long as it is not followed by a daily decline of more than 0.1 log cycle. The program then searches the array again, estimating by linear interpolation the ground-water discharge on days when surface runoff has occurred, then correcting any estimated ground-water discharge values that have exceeded the streamflow value for that day (Rutledge, 1998). Finally, the program writes the results to several output files, and calculates the mean base flow for the period of record being analyzed—in inches per year and as a percentage of the mean streamflow for the period (the base-flow index).

Program RORA

The program RORA (Rutledge, 1993, 1998, 2000) is a theoretically based procedure using the recession-curve-displacement method to estimate total ground-water recharge to a basin from daily mean values of streamflow. The recession-curve-displacement method (Meyboom, 1961) is based on the upward shift that occurs in the streamflow-recession curve in response to a recharge event. A recharge event will increase the total potential ground-water discharge from an aquifer to a stream, represented as V, which represents the total volume of water that will drain from the aquifer if allowed to do so for an infinite period without further recharge. Meyboom (1961) expressed V in the following equation, which is based on a linear relation between the logarithm of ground water discharge and time as:

$$V = \frac{Q \times K}{2.3026} \qquad (1)$$

where:

V = total potential ground-water discharge (L^3),
Q = ground-water discharge at an initial time (L^3/T), and
K = recession index, which is the time required for ground-water discharge to decline 1 log cycle after critical time (T_c).

The critical time (T_c) is the time necessary for the ground-water head distribution in a given aquifer to stabilize after a recharge event, after which time the logarithm of streamflow as a function of time is linear. Rorabaugh (1964) approximated critical time through the following equation as:

$$T_c = \frac{0.2\,(a^2)\,S}{Tr} \qquad (2)$$

where:

T_c = critical time (T)
a = average distance from the stream to the ground-water divide,
S = storage coefficient, and
Tr = transmissivity (L^2/T).

Rorabaugh (1964) showed that the total potential ground-water discharge to a stream at critical time (eq. 2) after a streamflow peak is approximately equal to half of the total volume of water that recharged the ground-water system during the peak. Therefore, total recharge is calculated in program RORA by the following equation (Rutledge, 1993) as:

$$R = \frac{2(Q_2 - Q_1)K}{2.3026} \qquad (3)$$

where:

R = total volume of recharge resulting from the precipitation event (L^3)
Q_1 = ground-water discharge at critical time, as extrapolated from the pre-event streamflow recession (L^3/T), and
Q_2 = ground-water discharge at critical time, as extrapolated from the post-event streamflow recession (L^3/T).

Rutledge (1993) derives an equation for critical time expressed as a function of recession index (K) by combining two equations to obtain:

$$T_c = 0.2144\,(K) \qquad (4)$$

The recession-curve-displacement method consists of the following steps, as illustrated in figure 10:

1. Compute the recession index (K) from the hydrograph during periods of no recharge
2. Compute the critical time (T_c) using equation 4.
3. Calculate the hypothetical ground-water discharge to the stream at T_c if recharge had not occurred by extrapolating the pre-event recession curve.
4. Calculate the ground-water discharge to the stream, including recent recharge, by extrapolating the post-event recession curve to T_c.
5. Solve equation 3 to obtain the recharge volume (R).

In practice, RORA first locates days in the streamflow record that fit an antecedent recession requirement, then identifies periods of ground-water recession, which can consist of one or more days that each fit the requirement. The program then defines a peak as the largest value of streamflow between two consecutive periods of ground-water recession and labels that peak as a recharge event. The program then estimates the ground-water recharge associated with each peak by using the recession-curve-displacement method (fig. 10). Finally, the program sums all of the calculated recharge volumes for the period of record being analyzed and calculates a mean recharge for the basin for the period of record, expressed in inches per year.

Precipitation, Recharge, and Base Flow, by Subbasin

Daily mean values of streamflow for the five gaged subbasins and one ungaged subbasin in the East Branch Delaware River Basin were compiled for 1998-2001, and daily mean discharge values for the two western gaged subbasins were compiled for 1945-52, as described earlier. These data were analyzed by two different methods, programs PART and RORA, to obtain estimates of mean annual base flow (equivalent to mean annual recharge) for each subbasin for the periods analyzed. Both estimates (table 3) are based on measured streamflow, and, therefore, should be considered net or effective ground-water recharge values, which exclude any recharge that may have been lost through evapotranspiration before reaching the streams.

Precipitation

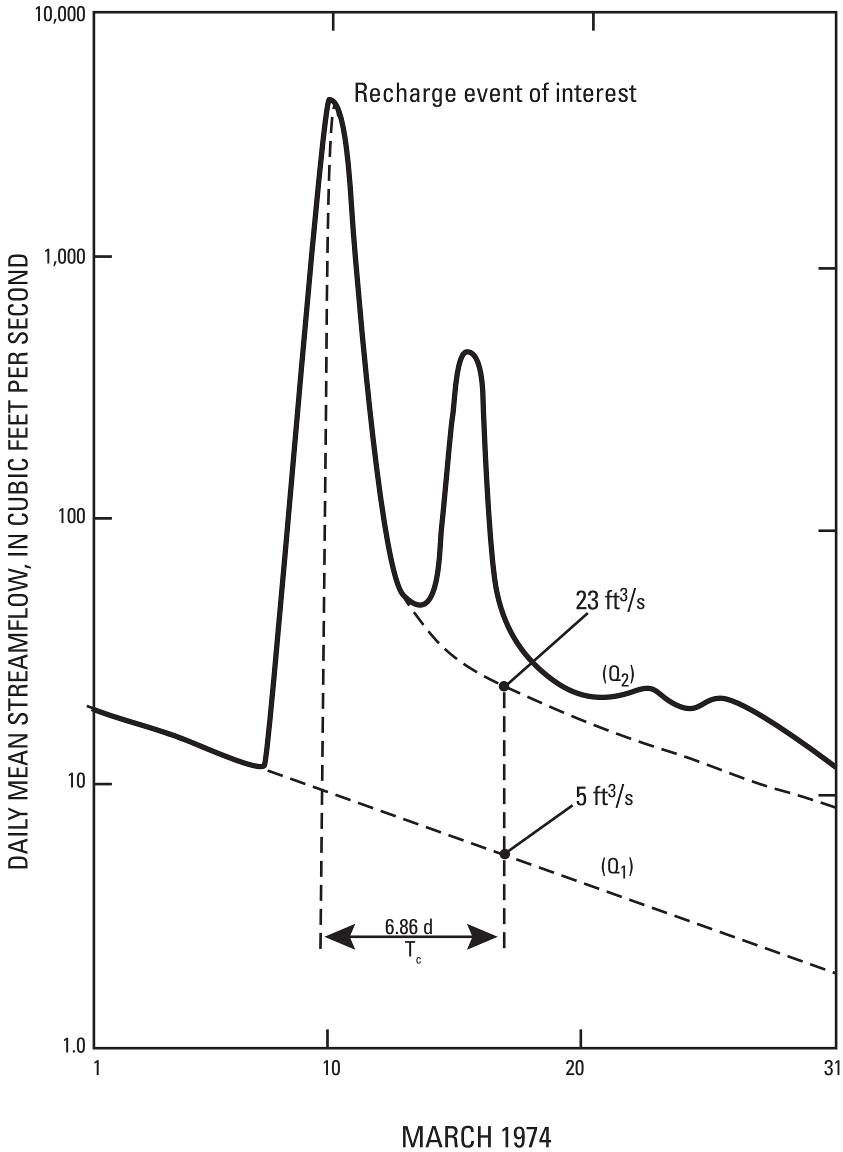
Data from a precipitation station at Arkville were obtained for each year from 1998 to 2001 from the Northeast Regional Climate Center database at Cornell University (http://climod.nrcc.cornell.edu). Mean annual precipitation for the Arkville station for this period was 42.25 in. This value compares favorably with the areal distribution of mean annual precipitation over the East Branch Delaware River Basin for the longer period 1951-80 as depicted in Randall (1996); therefore, the contours of mean annual precipitation in Randall were used as a guide to estimate the mean annual precipitation for each of the eight subbasins for 1998-2001. Mean precipitation for each subbasin was estimated as the sum of mean streamflow from gaging station records for 1998-2000, and mean evapotranspiration (ET), using data from Randall (1996). The resulting precipitation values, along with mean values for components of hydrologic budgets for the eight subbasins, are given in table 3. Long-term mean annual precipitation in the East Branch Delaware River Basin reflects the topography, and ranges from 40 in/yr in the valley at Margaretville and Dunraven to 55 in/yr in the higher altitudes of the Mill Brook subbasin (Randall, 1996). The distribution of mean annual precipitation, runoff, and zones of evapotranspiration within the East Branch Delaware River Basin is shown in figure 11.

Recharge

The estimates of mean annual recharge for the six eastern subbasins obtained through the RORA analysis for 1998-2001, and for the two western subbasins for 1945-52, range from 15.8 to 24.3 in/yr (table 3). The highest recharge rate is in the Mill Brook subbasin (station 01414500), which is also the subbasin with the greatest mean annual precipitation for 1998-2000 (50 in/yr). Several other subbasins have mean annual recharge rates in excess of 20 in/yr; these include Coles Clove Kill (23.07 in/yr), Terry Clove Kill (22.43 in/yr), and Dry Brook (20.10 in/yr). Recharge rates are determined primarily by the amount of precipitation, but are also affected by the hydraulic properties of the soil zone, the position of the water table with respect to land surface, the surface slope, and antecedent-soil moisture content. Programs RORA and PART, which use different mathematical procedures to estimate ground-water discharge as a surrogate for recharge, are essentially estimating the same parameter through two different forms of hydrograph separation. The results of the separate RORA and PART analyses conducted on the eight subbasins (nine gaging stations) are both included in table 3, however, for comparison.

Base Flow

Mean annual base-flow values for the two periods of record studied were calculated through streamflow partitioning (program PART) and are given in table 3. Mean annual base-flow values for the six eastern subbasins for 1998-2001 ranged from 15.31 in/yr for the Tremper Kill near Andes, N.Y. to 22.28 in/yr for Mill Brook at Dunraven, N.Y. Values of mean annual base flow for the two western subbasins for 1945-52 were 18.94 in/yr for Coles Clove Kill and 19.41 in /yr for Terry Clove Kill. A more useful statistic for use in comparing mean annual base flows of these eight subbasins is the “base-



EXPLANATION

[d, days; s, seconds; ft^3/s, cubic feet per second]

DAILY STREAMFLOW

EXTRAPOLATED GROUND-WATER DISCHARGE

PROCEDURE

1. Compute recession index, K (32d/ log cycle, in this example).
2. Compute critical time, T_c (0.2144 x K or 6.86 d).
3. Locate time that is 6.86 days after peak, as shown by arrow on figure.
4. Extrapolate pre-event recession to critical time; read $Q_1=5\ ft^3/s$.
5. Extrapolate post-event recession to critical time; read $Q_2=23\ ft^3/s$.
6. Compute total recharge, from equation 3.

$$R = \frac{2(Q_2 - Q_1)K}{2.3026} = \frac{2(18\ ft^3/s)32d}{2.3026} \; x \; \frac{86{,}400s}{1d} = 4.32x10^7\ ft^3$$

Figure 10. Procedure for use of the recession curve displacement method to estimate ground-water recharge in response to a recharge event (modified from Rutledge, 1993, fig. 6)

Table 3. Mean hydrologic-budget values for the eight subbasins (nine gaging stations) in the East Branch Delaware River Basin in southeastern New York, 1998-2001.

[mi^2, square miles; in/yr, inches per year; ft^3/s, cubic feet per second; $(ft^3/s)/mi^2$, cubic feet per second per square mile; $(in/mi^2)/yr$, inches per square mile per year. Locations are shown in fig. 9.]

Station name	Station number	Drainage area (mi^2)	Mean [1] precipitation (in/yr)	Mean [2] evapotranspiration (in/yr)	Mean [3] streamflow		Mean ground-water recharge rate (in/yr)	Mean base flow (in/yr)	Mean[3] direct runoff (in/yr)	Base flow index (percent)	Mean base flow $(ft^3/s)/mi^2$	Mean recharge $(in/mi^2)/yr$	Mean stream discharge $(ft^3/s)/mi^2$
					in/yr	ft^3/s							
Bush Kill	01413398	46.7	47	18.5	24.98	85.90	19.73	18.48	6.50	74.0	1.36	0.42	1.84
Dry Brook	01413408	82.2	48	18.5	27.35	165.52	20.10	18.99	8.36	69.4	1.40	.24	2.01
East Branch Delaware	01413500	163.0	46	18.5	25.17	301.99	19.53	17.88	7.29	71.0	1.32	.12	1.85
Upper East Branch Delaware	#	80.8	45	18.5	22.94	136.47	17.87	17.38	5.56	75.7	1.28	.22	1.69
Platte Kill	01414000	34.9	43	18.5	23.64	60.74	18.62	16.92	6.72	71.6	1.25	.53	1.74
Mill Brook	01414500	25.2	50	18.0	29.69	55.08	24.33	22.28	7.41	75.0	1.64	.97	2.19
Tremper Kill	01415000	33.2	43	19.0	20.77	50.76	15.80	15.31	5.46	73.7	1.13	.48	1.53
Terry Clove Kill*	01415500	13.6	44	19.0	27.66	27.69	22.43	19.41	8.25	70.2	1.43	1.65	2.04
Coles Clove Kill*	01416500	28.0	43	19.0	27.41	56.51	23.07	18.94	8.48	69.1	1.40	.82	2.02

[1] Mean precipitation for each subb asin estimated as sum of mean discharge (from gaging-station records for 1998-2001, except as noted) and evapotranspiration (based on 1951-80 data but assumed to vary little from year to year).

[2] Mean for 1951-80, from Randall (1996).

[3] Mean streamflow minus mean base flow equals mean direct runoff.

* Mean hydrologic-budget values for this subbasin calculated from annual hydrographs for 1945-52.

Mean daily discharge values for this subbsasin were calculated by subtracting the flow of station 01413408 (Dry Brook) from station 01413500 (East Branch Delaware).

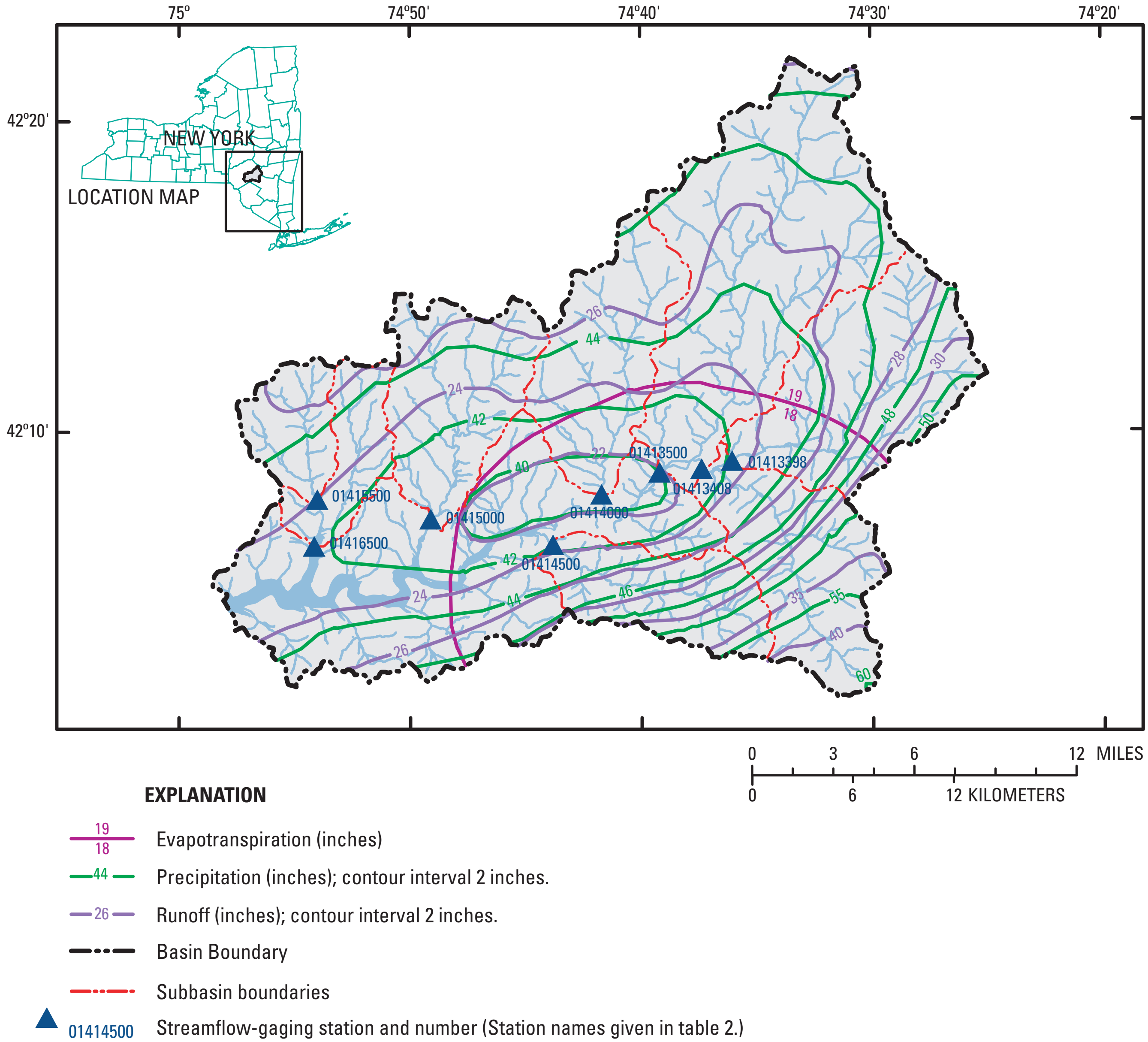


Figure 11. Distribution of mean annual precipitation, runoff, and zones of evapotranspiration within the East Branch Delaware River basin (modified from Randall, 1996).

flow index," which is the ratio of the mean annual base flow to the mean annual streamflow for each gaging station, expressed as percent. The base-flow indices for the eight subbasins (nine gaging stations) ranged from 69.1 percent for Coles Clove Kill to 75.7 percent for the Upper East Branch Delaware River. Mill Brook at Dunraven, N.Y. had the second-highest base-flow index (75 percent), which indicates that this basin has one of the highest base flows of the East Branch Delaware Basin, as well as the highest recharge rate (24.33 in/yr) and the highest mean annual streamflow (29.69 in/yr) of the basins analyzed.

A high base-flow index for a stream generally indicates that the basin contains a large amount of ground water in storage, generally in saturated stratified drift within the valley or in storage in fractured bedrock aquifers. Another statistic that indicates large ground-water storage within a given basin is the duration of base-flow recession. Coates (1971) developed base-flow recession curves for 25 basins in the Delaware and Susquehanna River Basins and, from these curves, calculated two indices that are a measure of the 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 its mean annual flow, and (2) the number of days required for flow to decline from 1 $(ft^3/s)/mi^2$ to 0.1 $(ft^3/s)/mi^2$. Both these indices of base-flow recession show that Mill Brook and East Branch Delaware River at Margaretville have among the longest base-flow recessions in the Catskills — 36.1 and 34.7 days, respectively, to decline from 1 $(ft^3/s)/mi^2$ to 0.1 $(ft^3/s)/mi^2$ (Coates, 1971, table 1; Reynolds, 2000, table 1). Only two other subbasins, the Beaver Kill at Craigie Claire and the Beaver Kill at Cooks Falls, display longer base-flow recessions; 37.6 and 36.7 days, respectively. Six of the eight subbasins (nine gaging stations) analyzed for this study were included in Coates's 1971 study; these are Terry Clove Kill, Coles Clove Kill, Mill Brook, Tremper Kill, Platte Kill, and East Branch Delaware River.

The results of the recession analysis (RECESS) performed on the eight East Branch Delaware subbasins (table 2) indicate similar results. The highest winter median recession indices, in days per log cycle of flow, were 61.9 days for Mill Brook at Dunraven (the station with the longest recession in the East Branch Delaware River Basin in Coates' 1971 study), and 65.6 days for Dry Brook (a tributary to the East Branch Delaware River at Margaretville), not analyzed by Coates.

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 ground water stored in stratified-drift aquifers that occupy the valley bottoms, or from partly saturated ice-contact deposits emplaced against valley walls (Wandle and Randall, 1994; Randall and Johnson, 1988; Coates, 1971). Coates (1971) delineated the percentage of land area occupied by stratified drift (valley fill) within each of 13 Catskill subbasins and found that stratified drift comprises only 2.9 percent of the Mill Brook subbasin and 5 percent of the East Branch Delaware River subbasin, which includes the upper East Branch Delaware, Bush Kill, and Dry Brook subbasins (Coates, 1971; Reynolds, 2000). The other Catskill subbasins studied by Coates had higher percentages of stratified drift, but yet had lower, and less sustained, base flows (Coates, 1971, table 1; Reynolds, 2000, table 1); therefore 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

One possible source of stream base flow is the bedrock that underlies these basins, particularly the Mill Brook, Bush Kill, Dry Brook, and Upper East Branch Delaware subbasins. Bedrock in the Catskill Mountains consists of sandstone, shale, and siltstone, of which sandstone is the most permeable because it contains extensive joints. 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 basins that he studied (Coates, 1971, table 1; Reynolds, 2000, table 1). The first, his "sandstone index," is the average percentage of sandstone present within measured stratigraphic sections within each subbasin; the second, his "massiveness index," is a measure of sandstone competency and fabric and is used to quantify the percentage of rock units as seen in outcrops that exceed 1 ft in thickness between bedding planes. Coates observed that the joints in the sandstones of the Catskill Mountains are larger and less numerous, but more continuous than those in the shale bedrock of the Susquehanna River basin to the west, and concluded that most of the sandstone within the 13 Catskill subbasins that he studied is massive and, therefore, would tend to have large, continuous joints that serve to transmit ground water. The highest sandstone indices of the 13 Catskill subbasins studied by Coates 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).

Of the East Branch Delaware River subbasins, Mill Brook has the highest sandstone index (91 percent), and the highest massiveness index (88 percent); the Tremper Kill had the next highest sandstone and massiveness indices of 88 and 79 percent, respectively. The remaining four East Branch Delaware River subbasins that were analyzed by Coates (1971) 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 high base-flow indices of 69 to 75 percent of total flow (table 3), 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). Coates (1971) has shown through statistical analysis that the sandstone index and the massiveness index show close correlation with the 90-percent flow duration (Q_{90}); the discharge that is exceeded 90 percent of the time, and a commonly used measure of base flow. 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 high base flows in the East Branch Delaware River subbasins, especially Mill Brook, may be wholly or partly derived from ground-water discharge from the jointed-sandstone aquifer. Reynolds (2000) reached this same conclusion concerning the adjacent Beaver Kill and Willowemoc Creek subbasins to the south.

Thick Till Deposits as a Source of Base Flow

The thick till that covers many upland areas in the East Branch Delaware River subbasins may seem to be a potential source of sustained stream base flow. Recent studies in New York and New England have shown, however, that the ground water in thick till deposits does not contribute appreciably to the base flow of streams in glaciated basins. Randall and Johnson (1988) present four low-flow equations, each one developed from a separate low-flow study in the glaciated Northeast, 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 ground-water contribution to streamflow.

A similar 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 ground-water discharge from coarse stratified drift was from 4 to 8 times greater than the ground-water discharge from till. Tills of New England generally have a much lower clay content and, thus, greater permeability, than those of New York, and this would imply that the relative amount of ground water discharged to streams from tills in New York would be much less than in New England. The results of these two studies (1) indicate that the large upland subbasins of ablation till within the East Branch Delaware River Basin probably contribute little ground-water discharge to the base flow of streams, and (2) provide additional evidence that the high base flows of the eight subbasins are derived from ground-water discharge from the underlying fractured and jointed sandstone.

Summary

The East Branch Delaware River Basin (Pepacton Reservoir watershed) drains about 372 mi^2 of the southwestern Catskill Mountains. The most widespread geologic unit within the basin is till, which occurs as masses of ablation till in major stream valleys and as thick deposits of lodgment till that partly fill upland basins. Till covers approximately 91.5 percent of the basin, and stratified drift, which consists of alluvium, outwash, and ice-contact deposits, accounts for 6.25 percent. The Pepacton Reservoir occupies about 2.25 percent of the basin area. Large outwash and ice-contact deposits occupy the valleys of the upper East Branch Delaware River, the Tremper Kill, the Platte Kill, the Bush Kill, and Dry Brook. These deposits form stratified-drift aquifers that range in thickness from 90 ft in parts of the upper East Branch Delaware River valley to less than 30 ft in the Dry Brook valley, and average about 50 ft for the main East Branch Delaware River valley near Margaretville.

Stream discharge records from the six eastern subbasins for 1998-2001, and the two western subbasins for 1945-52, were analyzed using computer programs to obtain estimates of mean annual base flow and mean annual ground-water recharge for each subbasin. Mean annual base flow ranged from 15.3 in/yr for the Tremper Kill subbasin to 22.3 in/yr for the Mill Brook subbasin; the latter reflects the highest mean annual precipitation of all subbasins studied. Estimated mean annual ground-water recharge ranged from 24.3 in/yr for Mill Brook subbasin to 15.8 in/yr for the Tremper Kill subbasin. The base-flow index, which is the mean annual base flow expressed as a percentage of mean annual streamflow, ranged from 69.1 percent for Coles Clove Kill to 75.7 percent for the upper East Branch Delaware River; most subbasin indices were greater than 70 percent.

Stratified drift, which is the principal source of base flow in most drainage basins in the northeastern United States, underlies only 5 to 7 percent of most gaged subbasins in the East Branch Delaware Basin; yet, the base-flow indices were high relative to gaged streams elsewhere with similar percentages of stratified drift. Therefore, it appears that the sandstone bedrock, which is recharged by abundant precipitation and discharges through numerous springs, is the probable source of most base flow in the East Branch Delaware River Basin.

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