In cooperation with the U.S. Environmental Protection Agency and the Delaware River Basin Commission

Effects of Land-Use Changes and Ground-Water Withdrawals on Stream Base Flow, Pocono Creek Watershed, Monroe County, Pennsylvania

Scientific Investigations Report 2008-5030

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

Cover photograph:
Pocono Creek watershed looking northeast from the top of Camelback Mountain.
Photograph by R.A. Sloto, U.S. Geological Survey.

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U.S. Geological Survey
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Conversion Factors and Datums

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	0.003785	cubic meter (m^3)
gallon (gal)	3.785	cubic decimeter (dm^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile [$(ft^3/s)/mi^2$]	0.01093	cubic meter per second per square kilometer [$(m^3/s)/km^2$]
gallon per minute (gal/min)	0.06309	liter per second (L/s)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
million gallons per year (Mgal/yr)	15.991	cubic meter per year (m^3/yr)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
	Specific capacity	
gallon per minute per foot [(gal/min)/ft)]	0.2070	liter per second per meter [(L/s)/m]
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Transmissivity*	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

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

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

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

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

Effects of Land-Use Changes and Ground-Water Withdrawals on Stream Base Flow, Pocono Creek Watershed, Monroe County, Pennsylvania

By Ronald A. Sloto

Abstract

The Pocono Creek watershed drains 46.5 square miles in eastern Monroe County, Pa. Between 2000 and 2020, the population of Monroe County is expected to increase by 70 percent, which will result in substantial changes in land-use patterns. An evaluation of the effect of reduced recharge from land-use changes and additional ground-water withdrawals on stream base flow was done by the U.S. Geological Survey (USGS) in cooperation with the U.S. Environmental Protection Agency (USEPA) and the Delaware River Basin Commission as part of the USEPA's Framework for Sustainable Watershed Management Initiative. Two models were used. A Soil and Water Assessment Tool (SWAT) model developed by the USEPA provided areal recharge values for 2000 land use and projected full buildout land use. The USGS MODFLOW-2000 ground-water-flow model was used to estimate the effect of reduced recharge from changes in land use and additional ground-water withdrawals on stream base flow. This report describes the ground-water-flow-model simulations.

The Pocono Creek watershed is underlain by sedimentary rock of Devonian age, which is overlain by a veneer of glacial deposits. All water-supply wells are cased into and derive water from the bedrock. In the ground-water-flow model, the surficial geologic units were grouped into six categories: (1) moraine deposits, (2) stratified drift, (3) lake deposits, (4) outwash, (5) swamp deposits, and (6) undifferentiated deposits. The unconsolidated surficial deposits are not used as a source of water. The ground-water and surface-water systems are well connected in the Pocono Creek watershed. Base flow measured on October 13, 2004, at 27 sites for model calibration showed that streams gained water between all sites measured except in the lower reach of Pocono Creek.

The ground-water-flow model included the entire Pocono Creek watershed. Horizontally, the modeled area was divided into a 53 by 155 cell grid with 6,060 active cells. Vertically, the modeled area was discretized into four layers. Layers 1 and 2 represented the unconsolidated surficial deposits where they are present and bedrock where the surficial deposits are absent. Layer 3 represented shallow bedrock and was 200 ft (feet) thick. Layer 4 represented deep bedrock and was 300 ft thick. A total of 873 cells representing streams were assigned to layer 1.

Recharge rates for model calibration were provided by the USEPA SWAT model for 2000 land-use conditions. Recharge rates for 2000 for the 29 subwatersheds in the SWAT model ranged from 6.11 to 22.66 inches per year. Because the ground-water-flow model was calibrated to base-flow data collected on October 13, 2004, the 2000 recharge rates were multiplied by 1.18 so the volume of recharge was equal to the volume of streamflow measured at the mouth of Pocono Creek. During model calibration, adjustments were made to aquifer hydraulic conductivity and streambed conductance. Simulated base flows and hydraulic heads were compared to measured base flows and hydraulic heads using the root mean squared error (RMSE) between measured and simulated values. The RMSE of the calibrated model for base flow was 4.7 cubic feet per second for 27 locations, and the RMSE for hydraulic heads for 15 locations was 35 ft.

The USEPA SWAT model was used to provide areal recharge values for 2000 and full buildout land-use conditions. The change in recharge ranged from an increase of 37.8 percent to a decrease of 60.8 percent. The ground-water-flow model was used to simulate base flow for 2000 and full buildout land-use conditions using steady-state simulations. The decrease in simulated base flow ranged from 3.8 to 63 percent at the streamflow-measurement sites. Simulated base flow at streamflow-gaging station Pocono Creek above Wigwam Run near Stroudsburg, Pa. (01441495), decreased 25 percent. This is in general agreement with the SWAT model, which estimated a 30.6-percent loss in base flow at the streamflow-gaging station.

Additional ground-water withdrawals were simulated in the Scot Run and Cranberry Creek subwatersheds for 2000 and full buildout land-use conditions. Hypothetical wells were added to each subwatershed to simulate additional ground-water pumping. Combined simulated pumpage from the wells ranged from 50,000 to 1,000,000 gallons per day. All pumpage was considered consumptive. In the Scot Run subwatershed, five hypothetical wells were placed close to the stream. With an additional 1 Mgal/d (million gallons per day) of ground-

water withdrawals, the simulated base flow of Scot Run decreased 36 percent under 2000 recharge conditions. Using the full buildout recharge rate, simulated base flow decreased 46 percent. With this distribution of wells, the base flow of adjacent Transue Run was not affected by ground-water withdrawals in the Scot Run subwatershed.

In the Cranberry Creek subwatershed, three hypothetical wells were placed close to the surface-water divide between Cranberry Creek and Bulgers Run, and three hypothetical wells were placed close to the surface-water divide between Cranberry Creek and Laurel Lake Run. With an additional 1 Mgal/d of ground-water withdrawals, the simulated base flow of Cranberry Creek decreased 15 percent, the simulated base flow of Bulgers Run decreased 14 percent, and the simulated base flow of Laurel Lake Run decreased 50 percent under 2000 recharge conditions. Simulated pumping wells close to the surface-water divide in the Cranberry Creek subwatershed had the least effect on the base flow of Cranberry Creek and the greatest effect on the base flow of Bulgers Run. Using the full buildout recharge rate, the simulated base flow of Cranberry Creek decreased 63 percent, the base flow of Bulgers Run decreased 60 percent, and the base flow of Laurel Lake Run decreased 96 percent from 2000 levels.

Introduction

Proximity to major population centers combined with natural beauty make tourism the number one industry in the Pocono Mountains (Poconos) region. The region is approximately 75 and 85 mi, respectively, from the New York City and Philadelphia metropolitan regions. The Poconos are the leading tourist destination in the Commonwealth of Pennsylvania. Gross revenues of tourism-related Pocono businesses, such as resorts, restaurants, and attractions, total more than $1.5 billion annually. Approximately 80 percent of the resorts in the Commonwealth of Pennsylvania are in the Poconos, and more than 18,000 people are employed by tourism-based businesses (The Insiders Guide, 2006).

One of the leading recreational activities in the Poconos is fishing. The area has an abundance of trout streams, considered to be among the finest in the nation. Trout season opens mid-April and extends throughout the majority of the year. Native brook and brown trout can be found in most streams.

The popularity of the Poconos as a second-home location has created a large demand for planned residential developments. Along with second-home owners, other Pocono residents who earn their living elsewhere are commuters. Monroe County is a preferred commuter residence because of the ease of access to major interstate highways. The Pocono Creek watershed (fig. 1) is bisected by U.S. Interstate 80 (fig. 2), which runs parallel to the creek. The county's primary commercial artery, Pennsylvania State Route 611, also runs parallel to Pocono Creek. Many people drive 1 to 2 hours each way to work in New Jersey or New York City. These commuters reap the dual benefits of higher-paying jobs available in those areas and the scenery and lifestyle of the Poconos (The Insiders Guide, 2006).

Monroe County is one of the fastest-growing counties in the Commonwealth of Pennsylvania. Between 2000 and 2006, the population of Monroe County increased 19.5 percent; the population of Pennsylvania increased 1.3 percent (U.S. Census Bureau, 2007). Between 2000 and 2020, the population of Monroe County is expected to increase by 70 percent (Monroe County Planning Commission, 2006). This population increase is expected to result in substantial changes in land-use patterns and an increased demand for water.

The overall objective of this study was to determine the effect of land-use changes and additional ground-water withdrawals on stream base flow. For this study, a regional numerical model of ground-water flow in the Pocono Creek watershed was developed as a tool to evaluate interactions between the ground-water and surface-water systems. This ground-water-flow-model study was done by the U.S. Geological Survey (USGS) in cooperation with the U.S. Environmental Protection Agency (USEPA) and the Delaware River Basin Commission (DRBC) as part of the USEPA's Framework for Sustainable Watershed Management Initiative. This study provides information that will allow the region's planners and local officials to make management decisions based on a quantitative understanding of the relations among base flow, ground-water withdrawal, and reduction in recharge caused by land-use changes. The results of this study are applicable to similar glaciated watersheds in northeastern Pennsylvania.

Purpose and Scope

This report describes the geology and ground-water-flow system of the Pocono Creek watershed in Monroe County, Pa., and presents the results of numerical simulation of ground-water flow in the Pocono Creek watershed. The model was used to simulate base-flow conditions on October 13, 2004; base flow under recharge conditions associated with 2000 land use; and base flow under potential recharge conditions associated with full buildout land-use conditions in the watershed. The model was used to estimate effects of potential reduction in recharge caused by land-use changes and ground-water withdrawals on stream base flow.

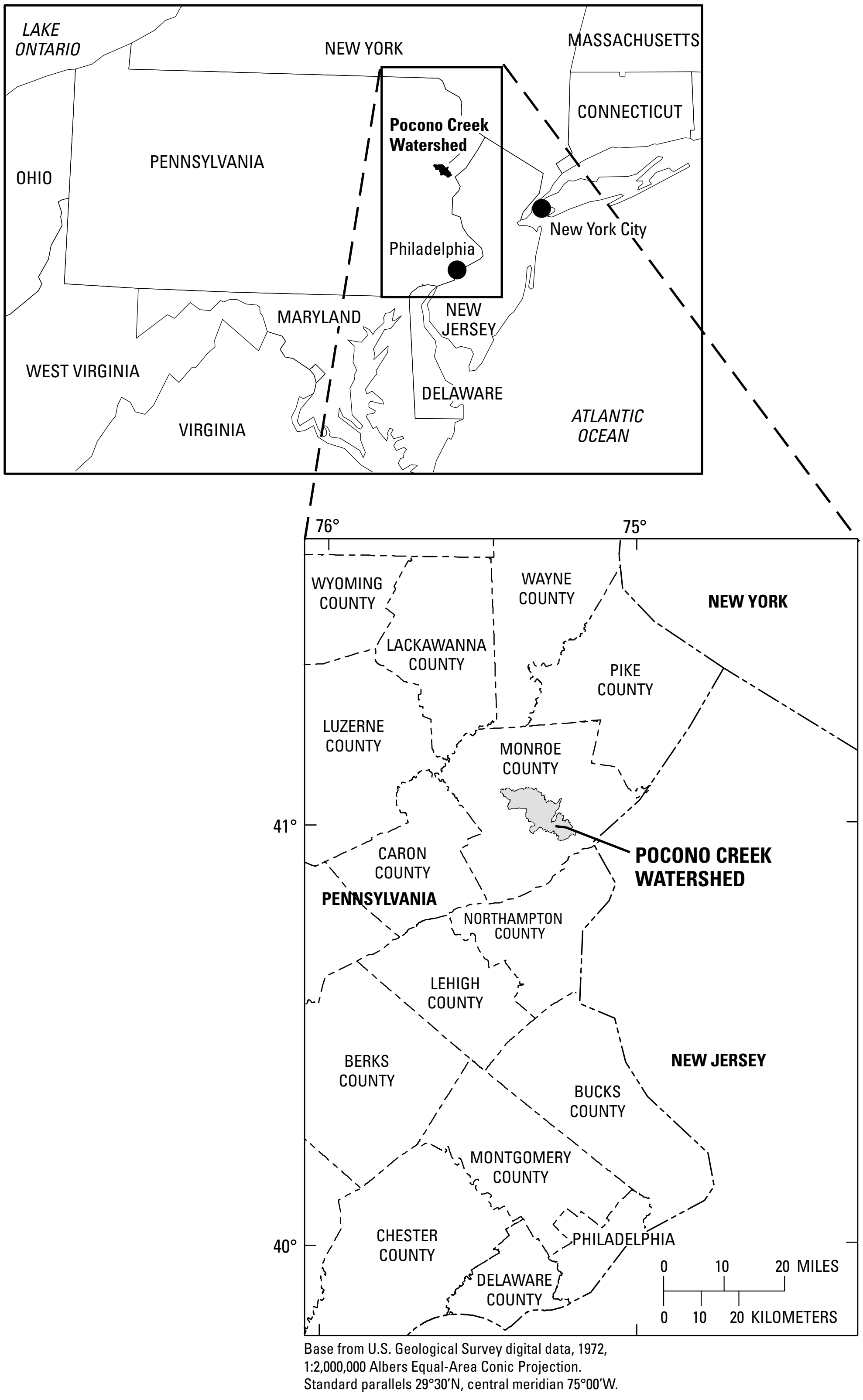


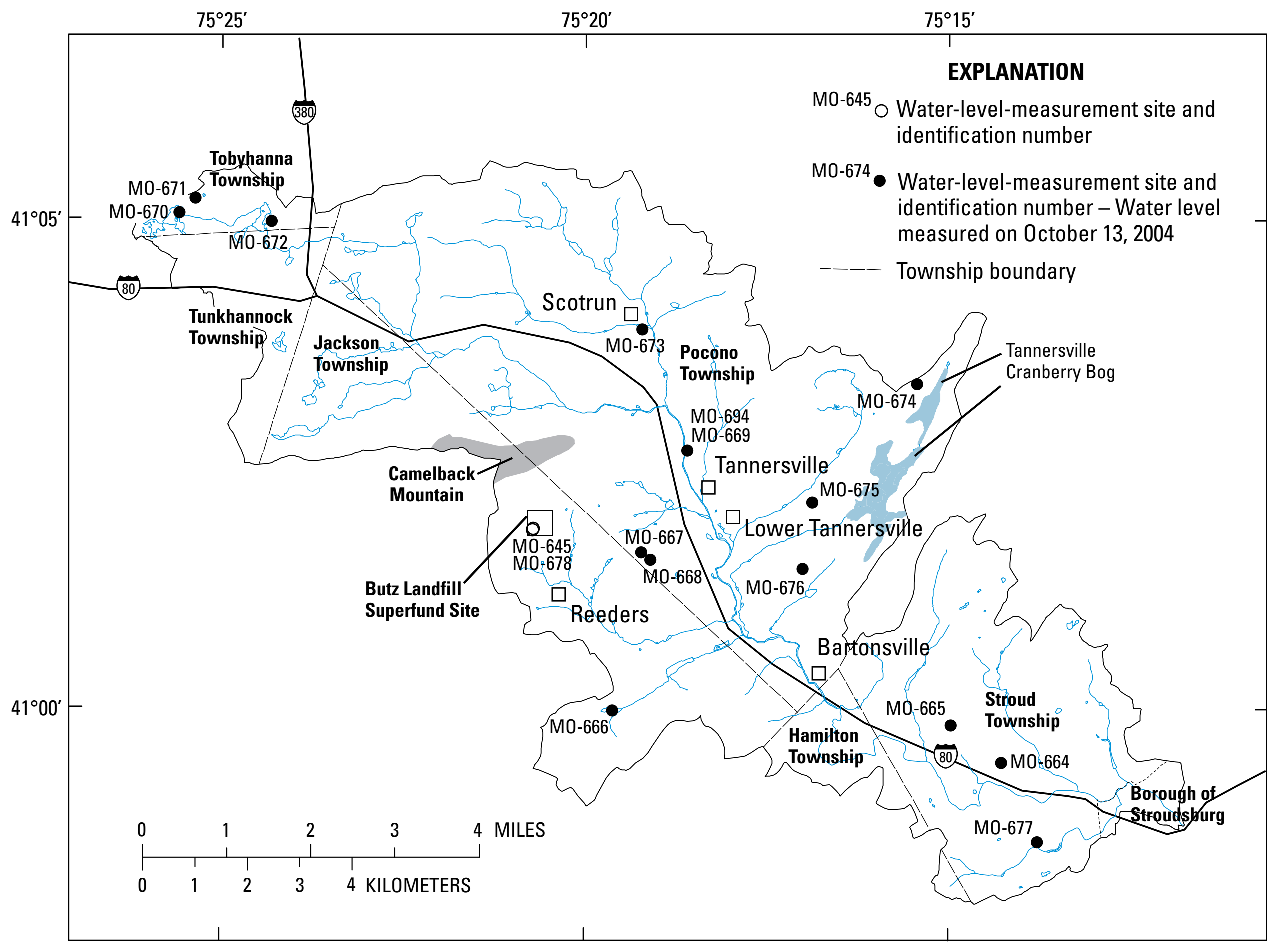
Figure 1. Location of the Pocono Creek watershed, Monroe County, Pa.

Description of Study Area

The Pocono Creek watershed drains 46.5 mi^2 in eastern Monroe County, Pa. (fig. 1). The watershed is entirely in Monroe County and includes parts of seven townships (fig. 2). Pocono Creek's 16-mi-long valley drains from the Pocono Plateau (fig. 3) in its headwaters to the Brodhead Creek, a tributary to the Delaware River. Tributaries to Pocono Creek include Dry Sawmill Run, Sand Spring Run, and Wolf Swamp Run in the north; Scot Run, Transue Run, Coolmoor Run, Mill Run, Reeders Run, Rocky Run, Bulgers Run, and Cranberry Creek in the mid-section; and Wigwam Run, Flagler Run, Big Meadow Run, and Little Pocono Creek in the lower third of the watershed (fig. 3). Sand Spring Run and Wolf Swamp Run are designated as Exceptional Value streams by the Pennsylvania Department of Environmental Protection. A streamflow-gaging station was established in June 2002 by the USGS on Pocono Creek just above its confluence with Wigwam Run (fig. 3).

Camelback Mountain (also called Big Pocono Mountain) is a prominent topographic feature in the watershed (fig. 2). The watershed also includes the Tannersville Cranberry Bog, which is the southernmost alpine boreal bog in the United States and is in the east-central part of the watershed. The Borough of Stroudsburg, one of the largest towns in the Pocono region and the Monroe County seat, is at the mouth of Pocono Creek.

The Pocono Creek watershed lies in three distinct physiographic province sections (fig. 3). The upper part is in the Glaciated Pocono Plateau Section of the Appalachian Plateaus Physiographic Province, the middle part is in the Glaciated Low Plateau Section of the Appalachian Plateaus Physiographic Province, and the lower part is in the Blue Mountain Section of the Ridge and Valley Physiographic Province (Sevon, 2000). The Pocono Plateau Escarpment sharply delineates the boundary between the Glaciated Low Plateau and



Base from U.S. Geological Survey digital data, 1972,
1:2,000,000 Albers Equal-Area Conic Projection.
Standard parallels 29°30′N, central meridian 75°00′W.

Figure 2. Political subdivisions in the Pocono Creek watershed, Monroe County, Pa.

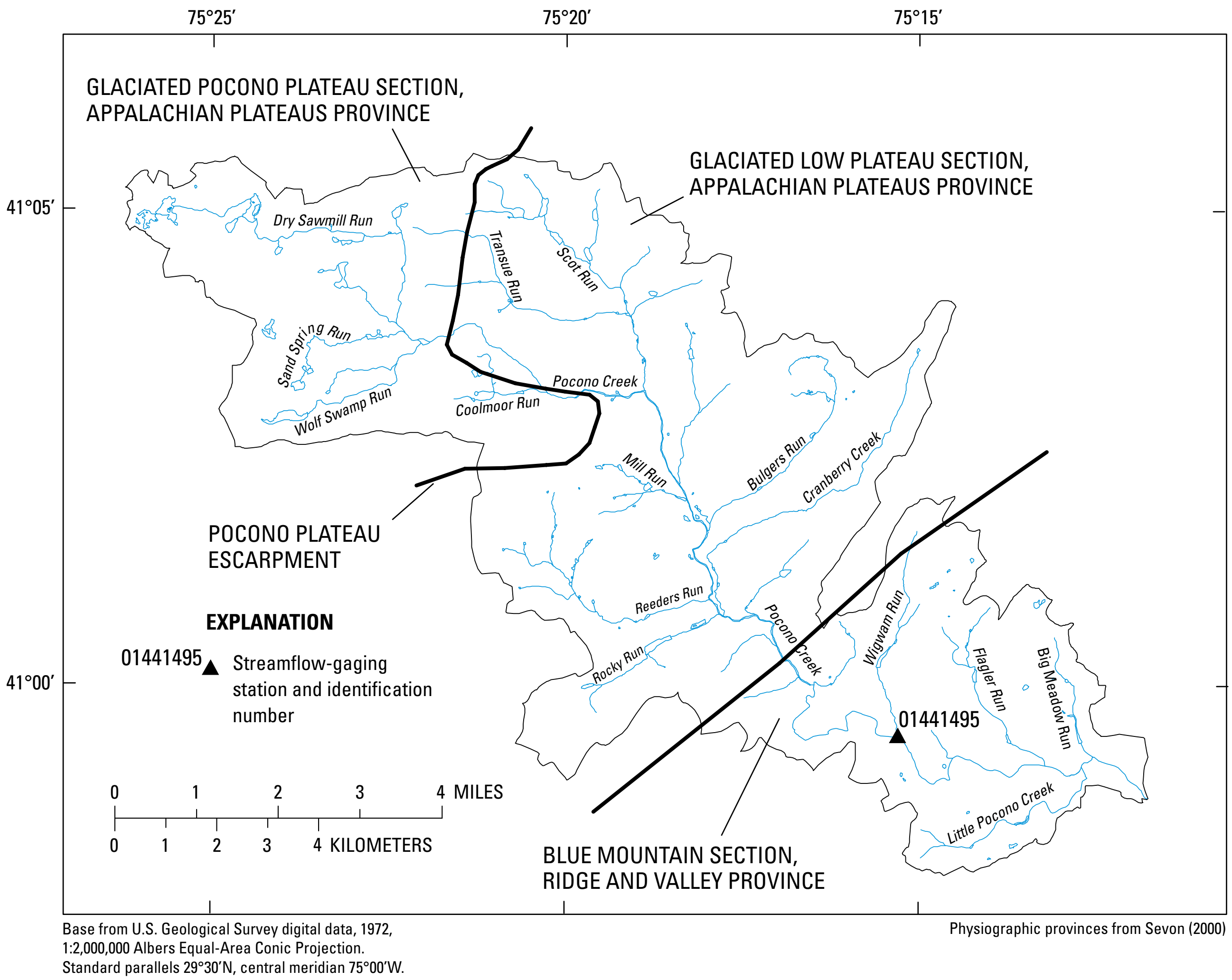


Figure 3. Physiographic provinces and streams in the Pocono Creek watershed, Monroe County, Pa.

Glaciated Pocono Plateau Sections. Rocks exposed west of the escarpment are more resistant to erosion than rocks exposed east of the escarpment. Local relief at Camelback Mountain, which is part of the Pocono Plateau Escarpment, is about 1,000 ft, the greatest anywhere along the escarpment.

The Pocono Plateau is relatively flat; local relief seldom exceeds 100 ft. The topography was greatly influenced by continental glaciation. The area is characterized by very irregular topography with numerous small, rounded hills separated by undrained depressions. The depressions generally are wet and often swampy (Berg and others, 1977).

Previous Investigations

The ground-water resources of Monroe County were described by Carswell and Lloyd (1979). Low and Conger (2001) provided an evaluation of borehole geophysical logs collected at the Butz Landfill Superfund Site. Water budgets were developed for the Pocono Creek watershed by Sloto and Buxton (2005). Streamflow statistics for Pocono Creek were determined by Thompson and Cavallo (2005).

The geology of the Pocono Creek area was first described by White (1882). Geology of the Pocono Pines and Mount Pocono quadrangles was mapped by Berg and others (1977), the Saylorsburg quadrangle by Epstein (1990), the Stroudsburg quadrangle by Epstein (1969, 1973), and the surficial geology of the East Stroudsburg quadrangle by Bucek (1971). This study builds on recent work by the DRBC and the Monroe County Conservation District to develop a goal-based watershed management plan for the Pocono Creek watershed (Delaware River Basin Commission, 2006a, 2006b).

Geology

The Pocono Creek watershed is underlain by sedimentary rocks of Devonian age (fig. 4) that are overlain by a veneer of glacial deposits. The sedimentary rocks record a general transition from marine to deltaic and finally to fluvial depositional environments. During the Pleistocene Epoch, continental glaciers repeatedly advanced southward from Canada across New York and covered the Pocono Creek watershed. The last advance of ice was about 15,000 years ago.

Bedrock Geology

The bedrock underlying the Pocono Creek watershed is mostly sandstone, siltstone, and shale of Devonian age. At the end of the Paleozoic Era, these rocks were broadly folded into a series of low-amplitude anticlines and synclines. Bedrock stratigraphy is presented in table 1.

Catskill Formation

Approximately three-fourths of the Pocono Creek watershed is underlain by rocks of the Catskill Formation. The Catskill Formation has been subdivided into several members. The members that underlie the Pocono Creek watershed are described in the following sections. Information presented is largely based on Berg and others (1977).

Poplar Gap Member

The Poplar Gap Member of the Catskill Formation is predominantly gray sandstone with some conglomeritic sandstone as discontinuous lenses and a few laterally discontinuous red siltstones and shales. It is a medium gray to light olive gray, thick-bedded, fine- to very coarse-grained sandstone. It was deposited by braided streams on a broad alluvial plain with occasional development of floodplains and deposition of overbank mud along short reaches of meandering streams. The Poplar Gap Member underlies the western part of the Pocono Plateau in the Pocono Creek watershed and crops out at the top of Camelback Mountain. It has been extensively modified by glacial erosion. The Poplar Gap Member is about 1,700 ft thick (Berg and others, 1977, p. 23-28).

Packerton Member

The Packerton Member of the Catskill Formation is predominantly sandstone with some conglomerate, siltstone, and shale. It is generally gray with a reddish tint. The Packerton Member was deposited as sands and gravels on an alluvial plain in a broad braided-river complex with local reaches of meandering streams that allowed deposition of overbank mud. The Packerton Member overlies the Poplar Gap Member. It is about 200 to 300 ft thick (Berg and others, 1977, p. 23-26).

Long Run Member

The Long Run Member of the Catskill Formation is alternating sandstone and fine red clastics in upward-fining sequences. It normally is a medium gray, medium- to thick-bedded, fine- to medium-grained sandstone. Upward-fining cycles of the Long Run Member result from fluvial deposition on a delta plain. The presence of marine fossils at the base of some cycles suggests deposition in tidally affected embayments of a lower delta plain. The Long Run Member forms the slope on the eastern and southern part of the Pocono Plateau below the Packerton Member. The calculated thickness of the Long Run Member is 3,175 ft, but it may exceed 3,500 ft (Berg and others, 1977, p. 19-23).

Table 1. Bedrock stratigraphy of the Pocono Creek watershed, Monroe County, Pa. From Berg and others (1983)

<table>
<tr><th>Series</th><th>Series</th><th colspan="2">Geologic unit</th></tr>
<tr><td rowspan="9">DEVONIAN</td><td rowspan="7">Upper</td><td rowspan="6">Catskill Formation</td><td>Poplar Gap Member</td></tr>
<tr><td>Packerton Member</td></tr>
<tr><td>Long Run Member</td></tr>
<tr><td>Beaverdam Run Member</td></tr>
<tr><td>Walcksville Member</td></tr>
<tr><td>Towamensing Member</td></tr>
<tr><td colspan="2">Trimmers Rock Formation</td></tr>
<tr><td rowspan="2">Middle</td><td colspan="2">Mahantango Formation of the Hamilton Group</td></tr>
<tr><td colspan="2">Marcellus Formation of the Hamilton Group</td></tr>
</table>

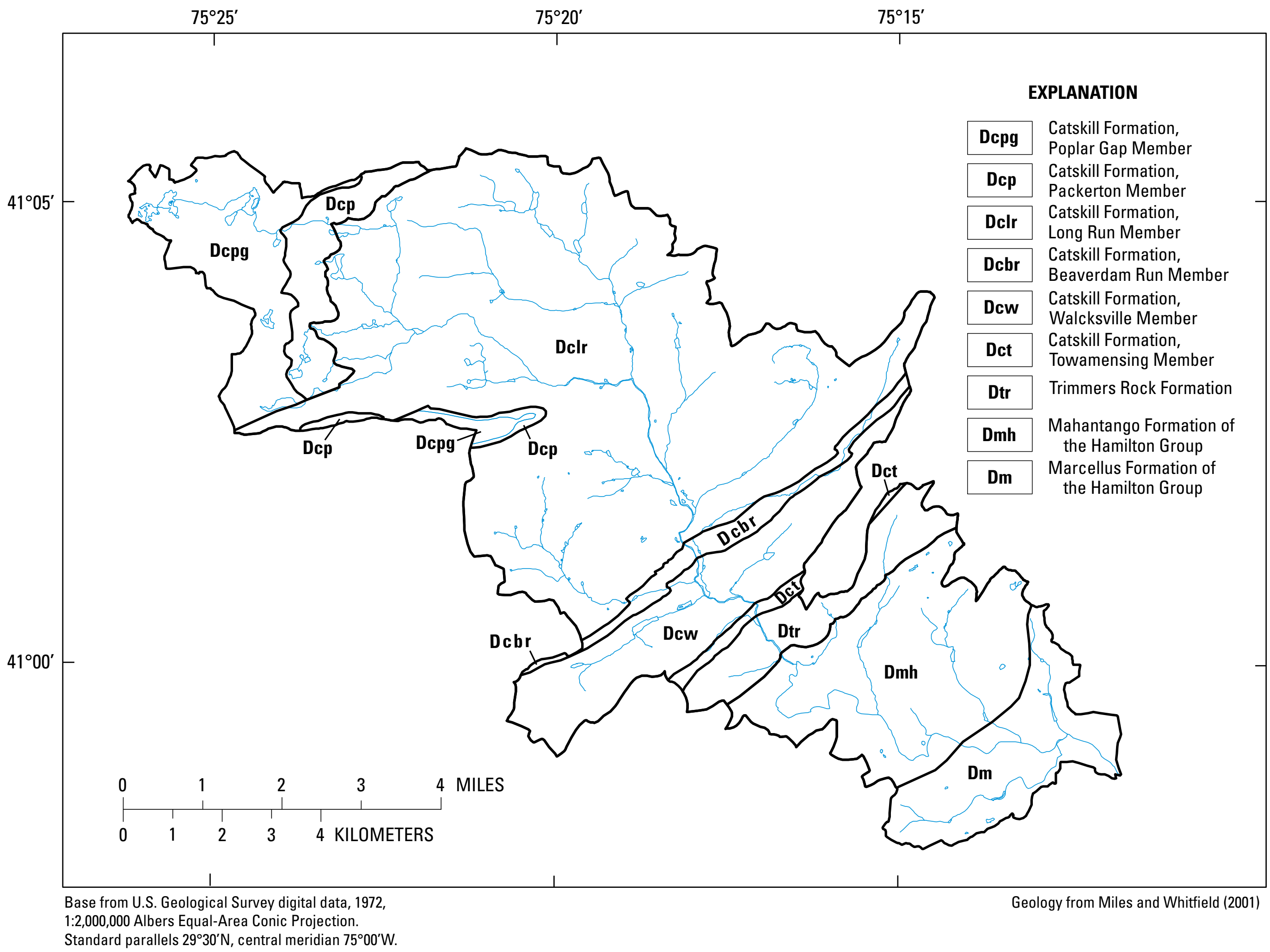


Figure 4. Bedrock geology in the Pocono Creek watershed, Monroe County, Pa.

Beaverdam Run Member

The Beaverdam Run Member of the Catskill Formation primarily is gray, medium- to thick-bedded, fine- to very fine-grained sandstone with some thin interbedded siltstone and silt shale, clay shale, and occasionally shale-chip conglomerate. The Beaverdam Run Member contains marine fossils, which suggest deposition in delta-front and offshore shelf-type environments. The average thickness is approximately 200 ft (Berg and others, 1977, p. 17-19).

Walcksville Member

The Walcksville Member of the Catskill Formation is alternating sandstone and shale in upward-fining sequences. The sandstone is medium gray, medium to thick bedded, and medium grained. The siltstones and shales are predominantly grayish red, nonfissile to subfissile, and thickly laminated to medium bedded. The upward-fining sequences of the Walcksville Member are the result of predominantly fluvial deposition in a delta plain. The Walcksville Member is approximately 1,000 ft thick (Berg and others, 1977, p. 14-16).

Towamensing Member

The Towamensing Member of the Catskill Formation is dominantly sandstone with some interbedded siltstone and silt shale. The sandstone is medium gray, medium to thick bedded, very fine to fine grained. The Towamensing Member was deposited in a lower delta to possible delta-front environment. It is in gradational contact with the underlying Trimmers Rock Formation. The Towamensing Member is about 500 ft thick (Berg and others, 1977, p. 11-13).

Trimmers Rock Formation

The Trimmers Rock Formation is dominantly interbedded siltstones and silt shale with some very fine sandstone in fining-upward turbidite cycles. It is a dark gray and medium dark gray, massive, nonfissile siltstone grading upward in cycles to fissile and subfissile shale and thick-bedded siltstones grading upward to thickly laminated shales. The depositional environment was distal to proximinal prodelta. The Trimmers Rock Formation is in gradational contact with the underlying Mahantango Formation and the overlying Towamensing Member. The Trimmers Rock Formation ranges from 950 to 1,175 ft thick and averages 1,060 ft thick. The variation in thickness is caused by minor folding (Berg and others, 1977, p. 6-10).

Mahantango Formation

The Mahantango Formation of the Hamilton Group is siltstone or silt shale. It is dark gray and medium dark gray, subfissile, and very thinly bedded to thickly laminated. It was deposited under open-water marine conditions with sufficient circulation and oxygenation for the establishment of diverse marine invertebrate communities (Berg and others, 1977, p. 5-6). Epstein (1990) estimated the Mahantango Formation to be about 2,000 ft thick.

Marcellus Formation

The Marcellus Formation of the Hamilton Group, called the Marcellus Shale by Epstein (1990), is a dark-gray, laminated to poorly bedded, silty shale. It grades upward to the Mahantango Formation. Epstein (1990) estimated the maximum thickness of the Marcellus Formation to be about 800 ft.

Surficial Geology

Northeastern Pennsylvania has been glaciated at least three times in the last 150,000 years. Each of these glaciations modified the landscape by erosion and deposition. Each successive ice sheet removed most, if not all, older glacial deposits, as well as some rock. The glaciations, from oldest to youngest, are Illinoian, Altonian (or pre-farmdalian Wisconsinan), and Woodfordian (late Wisconsinan) (Sevon and others, 1975, p. 9).

The glacial deposits can be broadly subdivided into stratified and unstratified deposits. The unstratified deposits mainly are till, which is composed of an unsorted mixture of clay, silt, sand, gravel, cobbles, and boulders deposited directly from the ice sheet as ground or end moraine. Stratified deposits of poorly to well-sorted sand, gravel, silt, and clay were transported and deposited by glacial meltwater. These deposits were formed in contact with the ice by streams flowing from the glacier as outwash in floodplains and deltas and as fine sediments in lakes and ponds formed as a consequence of glaciation (Carswell and Lloyd, 1979, p. 5).

Most of the Pocono Creek watershed is located on the Mount Pocono and Pocono Pines topographic quadrangle maps. The surficial geology of these quadrangles was mapped by Berg and others (1977). Epstein (1969) and Bucek (1971) mapped the surficial geology of the Stroudsburg and East Stroudsburg quadrangles, respectively. Epstein (1990) mapped the surficial geology of the Saylorsburg quadrangle. For this study, the surficial geology maps were combined (fig. 5) and generalized on the basis of textural composition (table 2) and hydraulic properties.

Outwash

Outwash includes the alluvium and Woodfordian outwash and the Woodfordian outwash of Berg and others (1977) and the outwash of Epstein (1969). Outwash consists of stratified, unconsolidated sand and gravel with some silt and clay and very few boulders in well-stratified units. Outwash was deposited by meltwater streams beyond the limit of the wasting ice sheet. It is confined to valleys that carried meltwater away from and behind the end moraine. The thickness ranges from 20 to 241 ft and averages about 60 to 65 ft (Berg and others, 1977, p. 42-43 and 50-51). The maximum depth of outwash reported by Berg and others (1977, p. 42) was 241 ft in the floodplain of Pocono Creek near Tannersville. Data collected for this study indicate the outwash in the Scot Run valley is up to 120 ft thick, and the outwash in the Pocono Creek valley is up to 122 ft thick and commonly is between 80 and 90 ft thick.

Ice-Contact Stratified Drift

Ice-contact stratified drift includes the alluvium and Woodfordian ice-contact stratified drift and Woodfordian ice-contact stratified drift of Berg and others (1977), the kame deposits of Epstein (1969) and Bucek (1971), and the kame terrace deposits and delta deposits of Epstein (1969). Ice-contact stratified drift consists of stratified, unconsolidated sand and gravel with some boulders. It frequently contains large masses of till. It forms subtle sheet-like deposits and subtly terraced valley-fill deposits. It was deposited during the stagnation and melting phase of the Woodfordian glacier in contact with the ablating ice lobe south of Camelback Mountain. Stratified drift is up to 100 ft thick and averages approximately 26 to 40 ft thick (Berg and others, 1977, p. 39-44 and 49-50).

Kame deposits consist of connected and isolated conical or irregularly shaped hills of well-sorted to poorly sorted and stratified sand, gravel, silt, and clay. Kame terrace deposits consist of stratified deposits of gravel, sand, and silt with some clay of variable sorting and stratification in flat-topped deposits against valley walls. They were laid down by meltwater between stagnant ice and adjacent valley walls. Delta deposits consist of gravel, sand, silt, and some clay that generally coarsen upward. Topset beds may contain rounded boulders up to 1 ft long. The foreset beds are finer than the topset beds and are well sorted. Foreset beds grade into glacial lake-bottom deposits.

Lake Deposits

Lake deposits are the glacial lake-bottom deposits described by Epstein (1969) and consist of varved clay, silt,

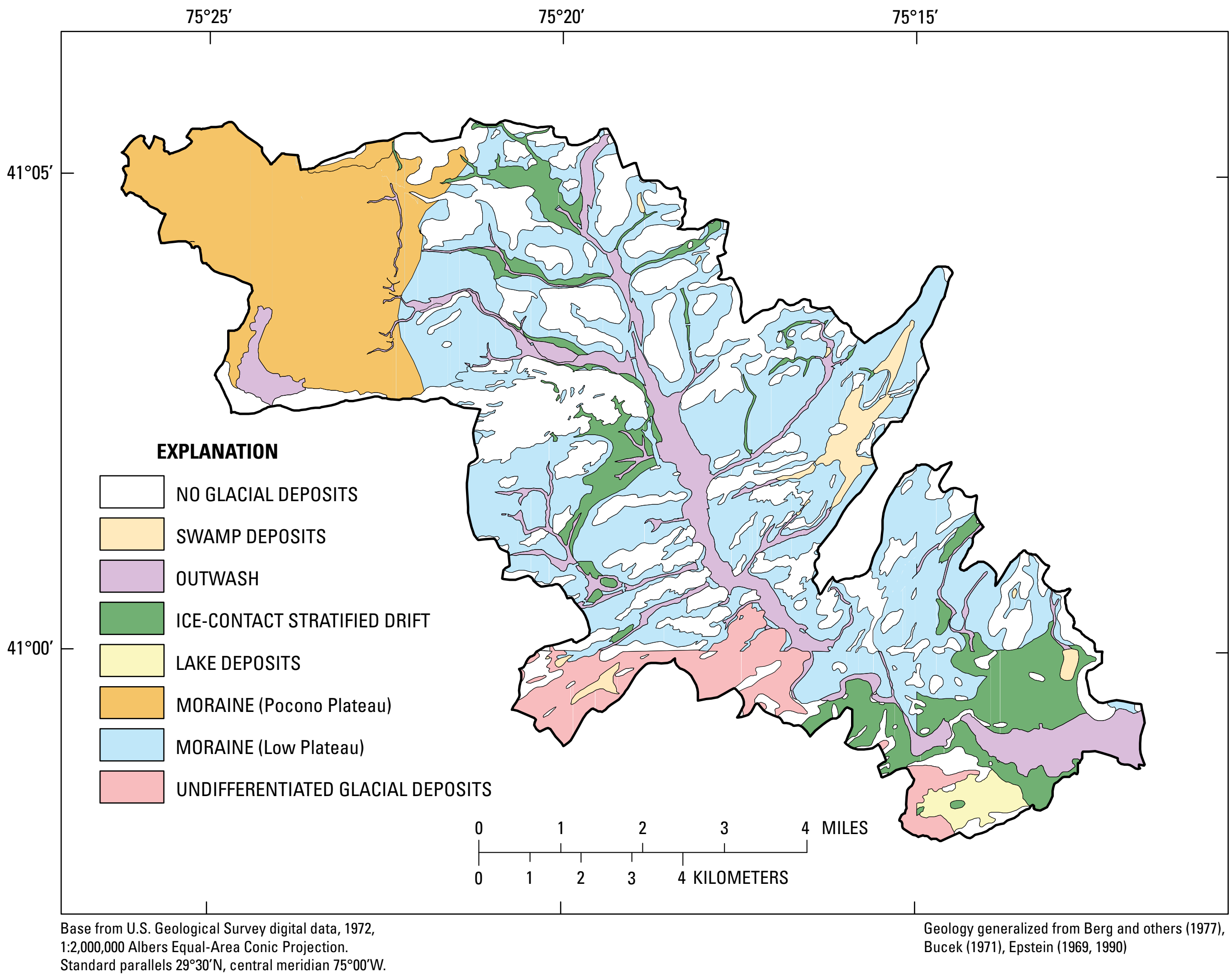


Figure 5. Generalized surficial geology in the Pocono Creek watershed, Monroe County, Pa.

Table 2. Mapped and generalized surficial geologic units in the Pocono Creek watershed, Monroe County, Pa.

<table>
<tr><th>This report</th><th>Berg and others (1977) Pocono Pines and Mount Pocono Quadrangles</th><th>Epstein (1969) Stroudsburg Quadrangle</th><th>Bucek (1971) East Stroudsburg Quadrangle</th><th>Epstein (1990) Saylorsburg Quadrangle</th></tr>
<tr><td rowspan="5">Undifferentiated deposits</td><td>Alluvium (Qal)</td><td>Alluvium (Qal)</td><td>Alluvium (Qal)</td><td rowspan="3">Alluvium (Qal)</td></tr>
<tr><td>Alluvium-colluvium undifferentiated (Qac)</td><td rowspan="4"></td><td rowspan="4"></td></tr>
<tr><td>Colluvium (Qc)</td></tr>
<tr><td>Boulder colluvium (Qbc)</td><td rowspan="2"></td></tr>
<tr><td>Talus (Qt)</td></tr>
<tr><td rowspan="2">Swamp deposits</td><td>Peat (Qp)</td><td rowspan="2">Swamp deposits (Qs)</td><td rowspan="2">Peat bog (Qpb)</td><td rowspan="2">Swamp deposits (Qs)</td></tr>
<tr><td>Swamp deposits (Qs)</td></tr>
<tr><td rowspan="2">Outwash</td><td>Alluvium and Woodfordian outwash, undifferentiated (Qwoa)</td><td rowspan="2">Outwash deposits (Qo)</td><td rowspan="2"></td><td rowspan="2"></td></tr>
<tr><td>Woodfordian outwash (Qwo)</td></tr>
<tr><td rowspan="4">Ice-contact stratified drift</td><td>Alluvium and Woodfordian ice-contact stratified drift, undifferentiated (Qwca)</td><td></td><td></td><td rowspan="8">Wisconsinan glacial deposits, undifferentiated (Qg)</td></tr>
<tr><td rowspan="4">Woodfordian ice-contact stratified drift (Qwic)</td><td>Delta deposits (Qd, Qe)</td><td></td></tr>
<tr><td>Kame deposits (Qk)</td><td>Kame deposits (Qk)</td></tr>
<tr><td>Kame terrace deposits (Qkt)</td><td rowspan="2"></td></tr>
<tr><td>Lake deposits</td><td>Glacial lake-bottom deposits (Ql)</td></tr>
<tr><td rowspan="6">Moraine deposits</td><td>Woodfordian ground moraine (Qwgm)</td><td>Ground moraine (Qgm)</td><td>Ground moraine (Qgm)</td></tr>
<tr><td>Woodfordian drumlinoid moraine (Qwdm)</td><td rowspan="5"></td><td>Drumlinoid till ridges (Qdm)</td></tr>
<tr><td>Woodfordian end moraine (Qwem)</td><td rowspan="4"></td></tr>
<tr><td>Altonian till and colluvium (Qatc)</td><td rowspan="3"></td></tr>
<tr><td>Illinoian till and colluvium, undifferentiated (Qifc)</td></tr>
<tr><td>Illinoian till (Qit)</td></tr>
</table>

and fine sand deposited on the floor of a temporary glacial lake. The deposits include some interbedded sand and gravel. They are horizontally stratified, rhythmically bedded, and laminated.

Swamp Deposits

Swamp deposits include the swamp deposits and peat described by Berg and others (1977), the swamp deposits described by Epstein (1969, 1990), and the peat bogs described by Bucek (1971). Swamp deposits consist of unconsolidated, stratified clay, silt, and sand mixed with muck, sometimes covered with a veneer up to 2 ft thick of waterlogged peat or muck. They were deposited in basins during the Woodfordian glaciation and thereafter by low-velocity meltwater and subsequent intermittent low-gradient streams. Swamp deposits are 2 to 30 ft thick (Berg and others, 1977, p. 46-47). Peat is water-saturated, fibrous and woody organic material composed of decayed sedges, reeds, rushes, mosses, shrubs, and trees. The upper part of a peat deposit sometimes is black peat humus. Peat is the product of partial decay of plants in poorly drained areas where dead organic material accumulates below water level. Peat occurs in level, undrained, or poorly drained swampy areas in natural lowland depressions (Berg and others, 1977, p. 46-49). The peat in the Tannersville Bog on Cranberry Creek is 47 ft thick (Jack McCormick and Associates, Inc., 1977). Cameron (1970, p. 19) noted that peat deposits form in closed depressions when clay, washed in from the sides of a water-filled depression, accumulates on the bottom. Most peat deposits form in places originally occupied by ponds after glacial retreat.

Moraine Deposits

Moraine deposits consist of the Illinoian till, Illinoian till and colluvium, Altonian till and colluvium, Woodfordian end moraine, Woodfordian drumlinoid moraine, and Woodfordian ground moraine of Berg and others (1977). Illinoian till consists of an unconsolidated, nonstratified, unsorted mixture of clay, silt, sand, pebbles, cobbles, and some boulders 1 to 2 ft in diameter. It was deposited by continental glaciation about 50,000 years ago. It was subsequently deeply weathered during the interglacial period and colluviated during Wisconsinan time. The thickness ranges from 0 to 120 ft and averages 20 to 50 ft (Berg and others, 1977, p. 30-32).

Altonian till consists of till with sandstone and conglomerate boulders 6 in. to 2 ft in diameter mixed with the upper 2 to 4 ft of deposits. The till is an unconsolidated, nonstratified, unsorted mixture of clay, silt, sand, pebbles, cobbles, and some boulders. The till was deposited by Altonian glaciation probably during the early Wisconsinan. The thickness is variable and averages 20 to 60 ft (Berg and others, 1977, p. 32-33)

The Woodfordian end moraine consists of an unconsolidated, nonstratified, and unsorted mixture of clay, silt, sand, pebbles, cobbles, and boulders up to 6 ft in diameter. Generally, it is a sandy mixture with small to moderate amounts of clay and moderate to large amounts of material coarser than 3 in. in diameter. It also contains moderately to well-sorted, stratified layers of sand and gravel from less than 1 in. to several feet thick and commonly is inclined. The end moraine occurs as a zone of irregular topography with many undrained depressions; generally, the depressions are densely vegetated, usually wet, and often swampy. The Woodfordian end moraine was deposited by the Woodfordian glacier during the period of maximum southward ice advance about 15,000 years ago. The thickness ranges from 17 to 170 ft and averages 97 ft on the Pocono Plateau (Berg and others, 1977, p. 33-35).

The Woodfordian drumlinoid moraine consists of an unsorted, nonstratified mixture of clay, silt, sand, pebbles, cobbles, and boulders. The drumlinoid moraine is characterized by streamlined ridges with intervening longitudinal depressions. The average length of drumlinoid ridges is about 1 mi. Ridges average 60 to 80 ft above the surrounding terrain. Longitudinal depressions between ridges frequently are filled with peat. The largest depression is the Tannersville Bog (Cranberry Swamp). Woodfordian drumlinoid moraines cause the alignment of Wigwam Run, Cranberry Creek, and Bulgers Run. The drumlinoid moraine was formed a short distance behind the Woodfordian end moraine where the debris load became so great in comparison with carrying power of the ice sheet that till was deposited by lodgement. The preglacial topography, consisting of hills and ridges oriented at an acute angle to glacial flow, disrupted ice movement and contributed to the deposition of drumlinoid moraines. The maximum thickness is 208 ft, the average thickness probably is about 100 ft, and it thins to a feather edge along protruding bedrock hills (Berg and others, 1977, p. 36-37).

The Woodfordian ground moraine consists of an unsorted, nonstratified mixture of clay, silt, sand, pebbles, cobbles, and boulders. It was deposited beneath the continental ice sheet during glacial advance as compact lodgement till or left as less compact sandy ablation till during ice melting and regional deglaciation. The thickness is widely variable; it ranges from 3 to 75 ft thick and averages about 25 ft (Berg and others, 1977, p. 38-39).

Hydrology

All water-supply wells in the Pocono Creek watershed are cased into and derive water from the bedrock. The unconsolidated surficial deposits are not used as a source of water. In the bedrock units, ground water moves through a network of interconnecting secondary openings—fractures and joints. The permeability of the rock depends on the number of fractures, the size of the fracture openings, and the degree of interconnection of the fractures. Ground water may be confined locally. A well will flow when it penetrates a water-bearing zone with a hydraulic head greater than the land-surface elevation. In the unconsolidated surficial deposits, ground water occurs in and moves through the void spaces. Water in the surficial geologic units generally is under water-table conditions.

The uncased part of a well (open borehole) may penetrate several water-bearing zones that are each under a different hydraulic head. Where differences in hydraulic head exist between water-bearing zones, water in the well bore flows in the direction of decreasing head. This can cause water levels in some wells to be different than water levels in adjacent wells of different depths. Low and Conger (2001) collected borehole geophysical logs and heatpulse-flowmeter measurements in 27 wells 56 to 319 ft deep completed in the Long Run Member of the Catskill Formation at and near the Butz Landfill Superfund Site (fig. 2) in 1996 and 2000. The heatpulse flowmeter was used to measure the rate and direction of borehole flow under nonpumping conditions. No borehole flow was measurable in eight wells ranging from 101 to 248 ft deep. Upward borehole flow (upward vertical head gradient) was measured in six wells ranging from 56 to 248 ft deep. Downward borehole flow (downward vertical head gradient) was measured in 11 wells ranging from 95 to 319 ft deep. Both upward and downward borehole flow were measured in two wells that were 118 and 159 ft deep.

The principal components of flow to and from bedrock aquifers include (1) direct recharge from precipitation where bedrock units are exposed; (2) flow to and from overlying surficial units; (3) recharge from streams; (4) ground-water discharge to surface-water bodies, such as streams, lakes, and wetlands; and (5) evapotranspiration directly from the bedrock ground-water system. The principal components of flow to and from surficial aquifers include (1) direct recharge from precipitation where surficial units are exposed; (2) flow to and from underlying bedrock units; (3) recharge from streams, especially losing reaches in the lower part of the Pocono Creek valley; (4) ground-water discharge to surface-water bodies, such as streams, lakes, and wetlands; and (5) evapotranspiration directly from the surficial ground-water system (Kontis and others, 2004, p. 30-31).

Water-Level Fluctuations

Water levels fluctuate in response to recharge to the ground-water system from precipitation and discharge from the ground-water system to pumping wells, ground-water evapotranspiration, and streams. Water levels generally rise during November to May when ground-water evapotranspiration and soil-moisture evapotranspiration are at a minimum and recharge is at a maximum. Water levels generally decline during June to October when ground-water evapotranspiration and soil-moisture evapotranspiration are at a maximum and recharge is at a minimum. Water levels were measured in selected wells in the Pocono Creek watershed during 2004-06 (fig. 2). Wells in different parts of the Pocono Creek watershed and in different bedrock units have similar hydrographs (fig. 6).

Two sets of wells were measured where one well was completed in the surficial aquifer and one well was completed in the bedrock aquifer. One set of wells, MO-645 completed in bedrock and MO-678 completed in the surficial deposits, is near the Butz Landfill Superfund Site near Reeders, Pa. Water levels at this site were not affected by ground-water pumping. The hydrographs are similar and indicate a downward vertical hydraulic gradient (fig. 7). One set of wells, MO-669 and MO-694, is near Tannersville. Well MO-669 is open to the bedrock aquifer in a confined ground-water system, and the hydrograph shows that the water level was affected by ground-water pumping (fig. 8). The water level in well MO-694 in the surficial aquifer was not affected by pumping.

Ground-Water/Surface-Water Relations

The ground-water and surface-water systems are well connected in the Pocono Creek watershed. In most areas, streams act as drains for the ground-water system and gain water. In some places, such as the lower part of Pocono Creek, some stream reaches may lose water and recharge the ground-water system. Where stream reaches gain water, streamflow is composed of ground-water discharge (base flow) and surface (overland) runoff (fig. 9). The quantity of ground water discharged to streams is related directly to the altitude of the water table. The hydrograph from well MO-667 is similar to the hydrograph of base flow (fig. 9). Well MO-667 is a bedrock well on a hilltop, and water levels are not influenced by a stream. Base flow generally declines when ground-water levels decline and increases when ground-water levels increase. The time of lowest base flow generally coincides with the lowest ground-water levels. Precipitation from June through October generally produces little recharge and little increase in ground-water levels; most of the infiltrated precipitation replenishes soil moisture.

The streamflow hydrograph of Pocono Creek was separated into base-flow and surface-runoff components using the HYSEP computer program of Sloto and Crouse (1996). The local-minimum hydrograph-separation technique was used. Data were only available for the 2003, 2004, and 2005 calendar years. On the basis of hydrograph separations, the annual base flow of Pocono Creek measured at streamflow-gaging station Pocono Creek above Wigwam Run near Stroudsburg, Pa. (station number 01441495), was 28.2, 22.8, and 21.1 in. for 2003, 2004, and 2005, respectively. Base flow made up an average of 52 percent of streamflow.

Base flow was measured on October 13, 2004, at 27 sites in the Pocono Creek watershed for ground-water-flow-model calibration (table 3). Measurement sites are shown on figure 10. The measurements were made 15 days after precipitation at the end of a long base-flow recession period. Measurement error ranged from 5 to about 12 percent.

The base-flow measurements show streams in the Pocono Creek watershed gained water between all sites measured except in the lower reach of Pocono Creek between sites

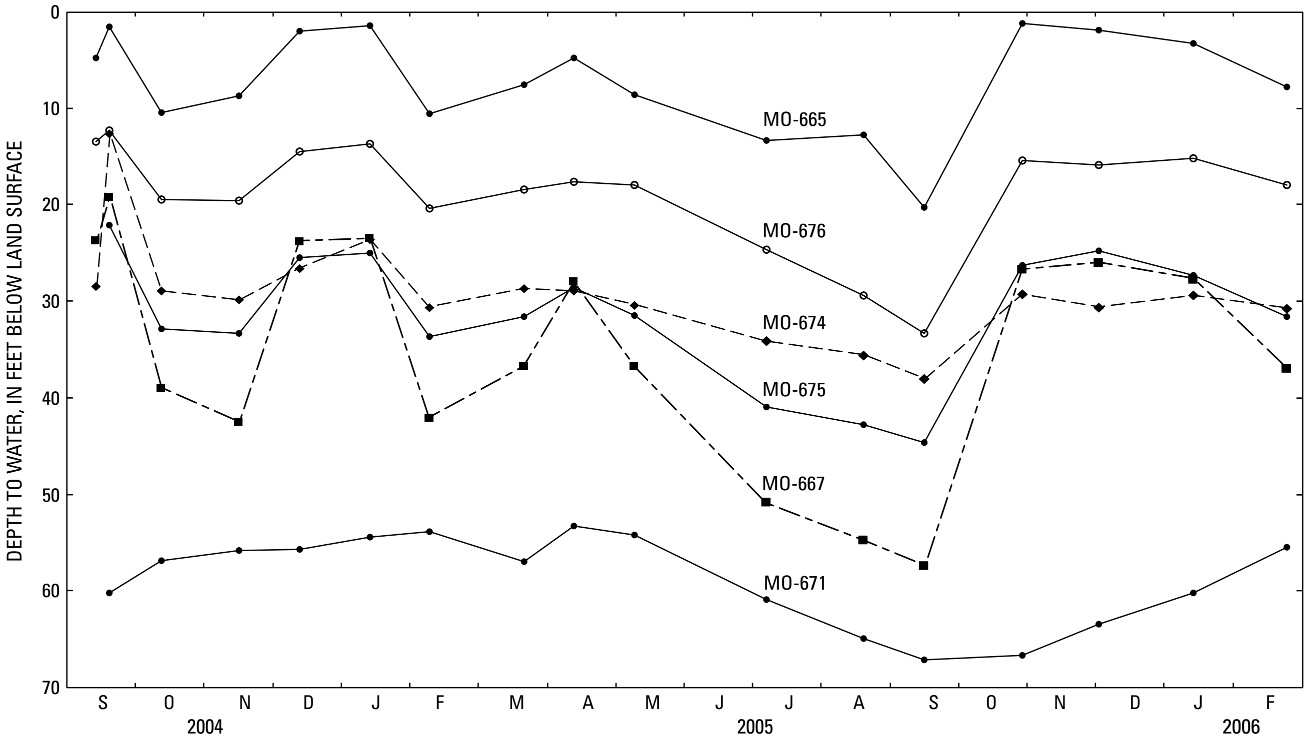


Figure 6. Hydrographs from selected bedrock wells in the Pocono Creek watershed, Monroe County, Pa. Well locations shown on figure 2.

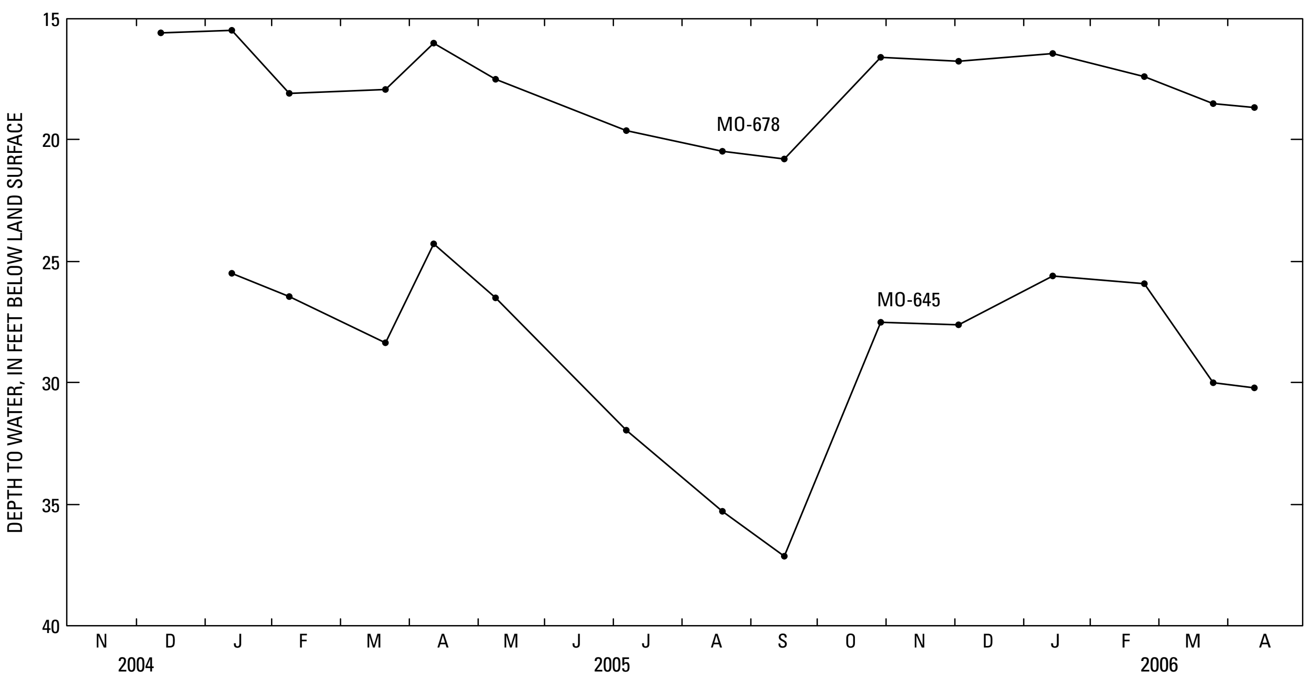


Figure 7. Hydrographs from well MO-645 open to the bedrock aquifer and well MO-678 open to the surficial aquifer near Reeders in the Pocono Creek watershed, Monroe County, Pa. Well locations shown on figure 2.

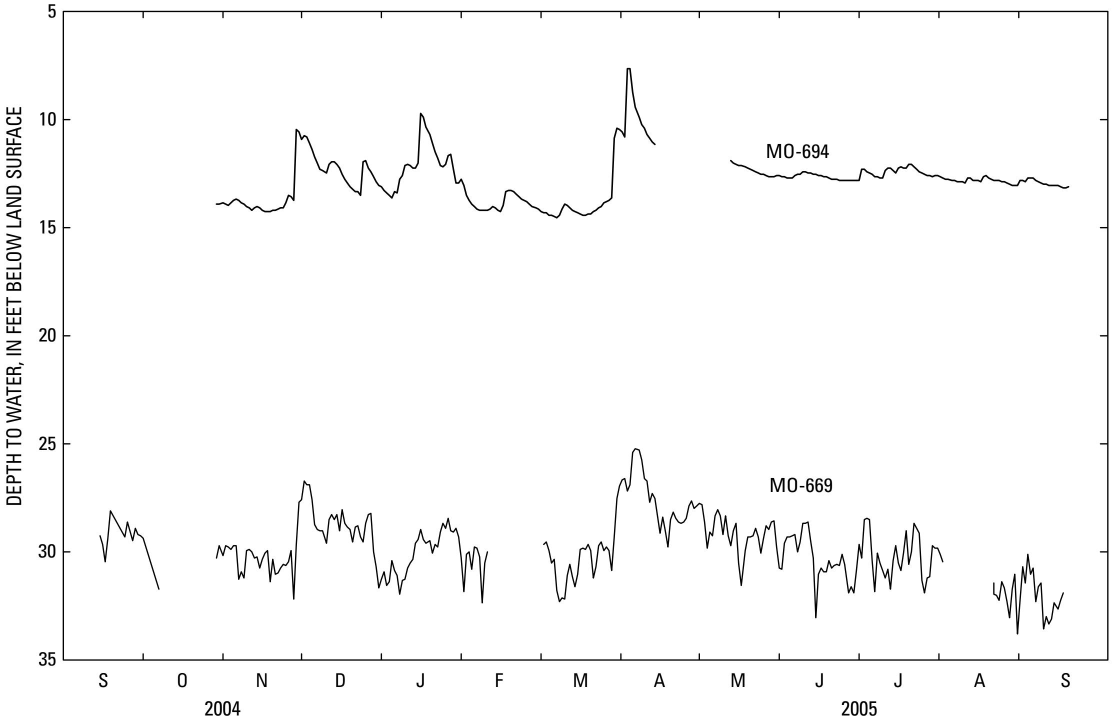


Figure 8. Hydrographs from well MO-669 open to the bedrock aquifer and well MO-694 open to the surficial aquifer near Tannersville in the Pocono Creek watershed, Monroe County, Pa. Gaps represent missing record. Well locations shown on figure 2.

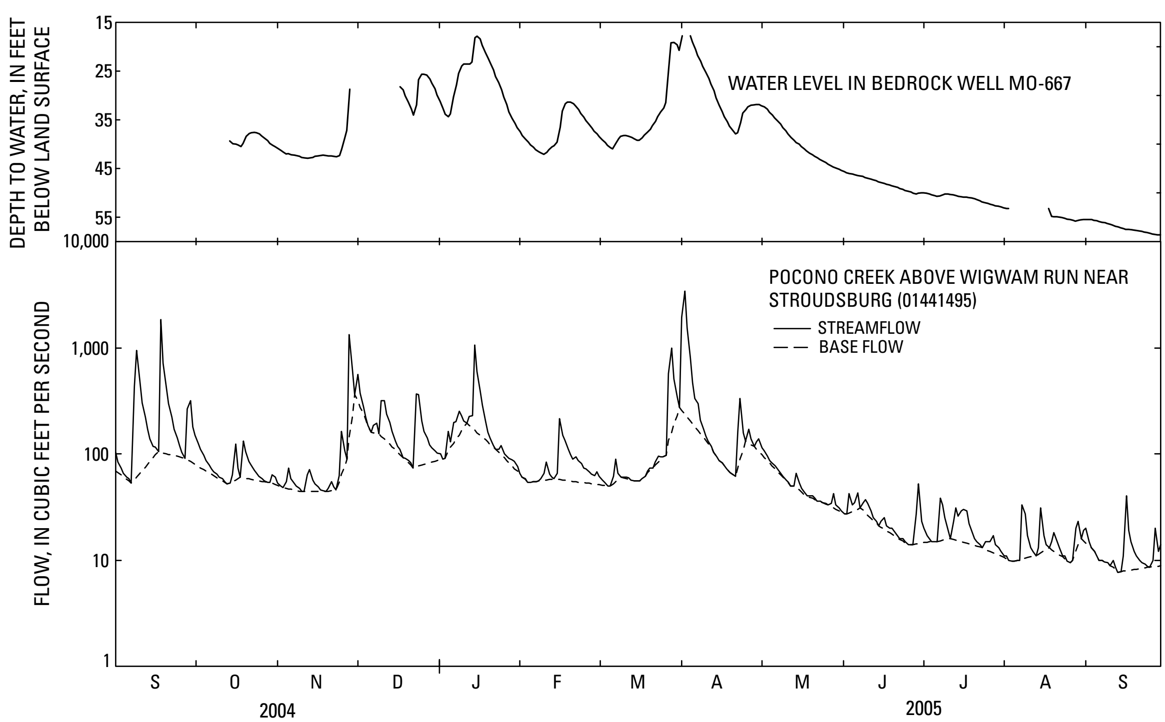


Figure 9. Relation among streamflow, base flow, and ground-water levels in the Pocono Creek watershed, Monroe County, Pa. Gaps represent missing record. Location of well MO-677 shown on figure 2. Location of streamflow-gaging station shown on figure 3.

Table 3. Base-flow measurements in the Pocono Creek watershed, Monroe County, Pa., October 13, 2004. Locations of measurement sites are shown on figure 10.

[lat, latitude; long, longitude; mi², square miles; ft, feet; ft³/s, cubic feet per second; >, greater than]

Measurement site identification number and stream	Location	Drainage area (mi²)	Base flow (ft³/s)	Measurement error (percent)
01441034 Dry Sawmill Run	Lat 41°04’45”, long 75°23’51”, 10 ft downstream of bridge on Granite Road at Crescent Lake, Pa.	2.51	0.35	5
01441042 Dry Sawmill Run	Lat 41°04’43”, long 75°22’38”, 50 ft downstream of bridge on Skyview Road at Crescent Lake, Pa.	3.28	1.5	8
01441154 Pocono Creek	Lat 41°03’42”, long 75°21’37”, 300 ft downstream of bridge on Wilke Road near Scotrun, Pa.	8.65	16	8
01441160 Pocono Creek	Lat 41°03’13”, long 75°20’27”, 30 ft downstream of bridge on Camelback Road near Scotrun, Pa.	9.24	17	8
01441178 Coolmoor Run	Lat 41°03’04”, long 75°20’19”, 50 ft above confluence with Pocono Creek near Scotrun, Pa.	1.50	3.2	8
01441190 Pocono Creek	Lat 41°03’03”, long 75°19’17”, 40 ft downstream of bridge on Sullivan Trail Road near Tannersville, Pa.	11.5	18	5
01441225 Scot Run	Lat 41°04’02”, long 75°19’11”, 200 ft downstream of bridge on State Route 611 at Scotrun, Pa.	3.23	4.2	8
01441245 Transue Run	Lat 41°03’ 5”, long 75°19’20”, 25 ft downstream of private bridge 700 ft above Scotrun Avenue at Scotrun, Pa.	2.07	2.5	8
01441255 Scot Run	Lat 41°03’35”, long 75°19’00”, 100 ft downstream of bridge on Scot Run Avenue at Scotrun, Pa.	6.10	7.2	8
01441261 Pocono Creek	Lat 41°02’37”, long 75°18’39”, 200 ft downstream of bridge on State Route 715 at Tannersville, Pa.	18.8	28	5
01441275 Highwood Lake Run	Lat 41°02’09”, long 75°18’24”, 15 ft downstream of culvert on Alger Road at Tannersville, Pa.	1.50	1.2	>8
01441295 Mill Run	Lat 41°02’01”, long 75°18’35”, 30 ft downstream of bridge on Old Mill Drive at Tannersville, Pa.	1.47	1.3	8
01441342 Bulgers Run	Lat 41°01’42”, long 75°17’58”, 30 ft upstream of bridge on Learn Road at Lower Tannersville, Pa.	2.25	3.0	8
01441350 Pocono Creek	Lat 41°01’24”, long 75°18’12”, 120 ft upstream of bridge on Stadden Road near Tannersville, Pa.	25.2	44	8
01441360 Reeders Run	Lat 41°00’42”, long 75°19’08”, 40 ft downstream of bridge on Reeders Run Road near Reeders, Pa.	2.88	3.1	8
01441369 Rocky Run	Lat 41°00’34”, long 75°18’16”, 75 ft downstream of bridge on Glenbrook Drive near Bartonsville, Pa.	2.03	1.9	>8
01441376 Cranberry Creek	Lat 41°01’27”, long 75°17’53”, 20 ft upstream of bridge on State Route 611 at Lower Tannersville, Pa.	2.54	2.4	>8
01441386 Laurel Lake Run	Lat 41°00’54”, long 75°17’21”, 20 ft upstream of bridge on Beehler Road at Bartonsville, Pa.	.76	.80	5
01441382 Pocono Creek	Lat 41°00’42”, long 75°17’30”, 300 ft downstream of bridge on State Route 611 near Bartonsville, Pa.	34.3	44	5
01441390 Pocono Creek	Lat 41°00’12”, long 75°16’48”, 100 ft upstream of bridge at Rimrock Drive at Bartonsville, Pa.	36.3	52	5
01441495[1] Pocono Creek	Lat 40°59’27”, long 75°15’20”, 25 ft downstream of bridge on Schafers School House Road near Stroudsburg, Pa.	38.9	61	5
01441498 Wigwam Run	Lat 40°59’44”, long 75°15’25”, 15 ft downstream of bridge on Schafers School House Road near Bartonsville, Pa.	1.66	1.5	8
01441500 Pocono Creek	Lat 40°59’10”, long 75°13’35”, at bridge on Bridge Street near Stroudsburg, Pa.	41.0	58	5
01441600 Flagler Run	Lat 40°59’15”, long 75°13’19”, 300 ft downstream of bridge on State Route 611 near Stroudsburg, Pa.	1.87	1.6	8

Table 3. Base-flow measurements in the Pocono Creek watershed, Monroe County, Pa., October 13, 2004.—Continued
Locations of measurement sites are shown on figure 10.

[lat, latitude; long, longitude; mi², square miles; ft, feet; ft³/s, cubic feet per second; >, greater than]

Measurement site identification number and stream	Location	Drainage area (mi²)	Base flow (ft³/s)	Measurement error (percent)
01441700 Little Pocono Creek	Lat 40°58'44", long 75°13'25", downstream of bridge on Tanite Road near Stroudsburg, Pa.	1.21	1.0	8
01441894 Big Meadow Run	Lat 40°59'20", long 75°12'41", 40 ft upstream of bridge on State Route 611 near Stroudsburg, Pa.	1.62	1.7	>8
01441896 Pocono Creek	Lat 40°59'14", long 75°12'28", 500 ft below confluence with Little Pocono Creek at Stroudsburg, Pa.	47.7	64	5

[1]Continuous-record streamflow-gaging station.

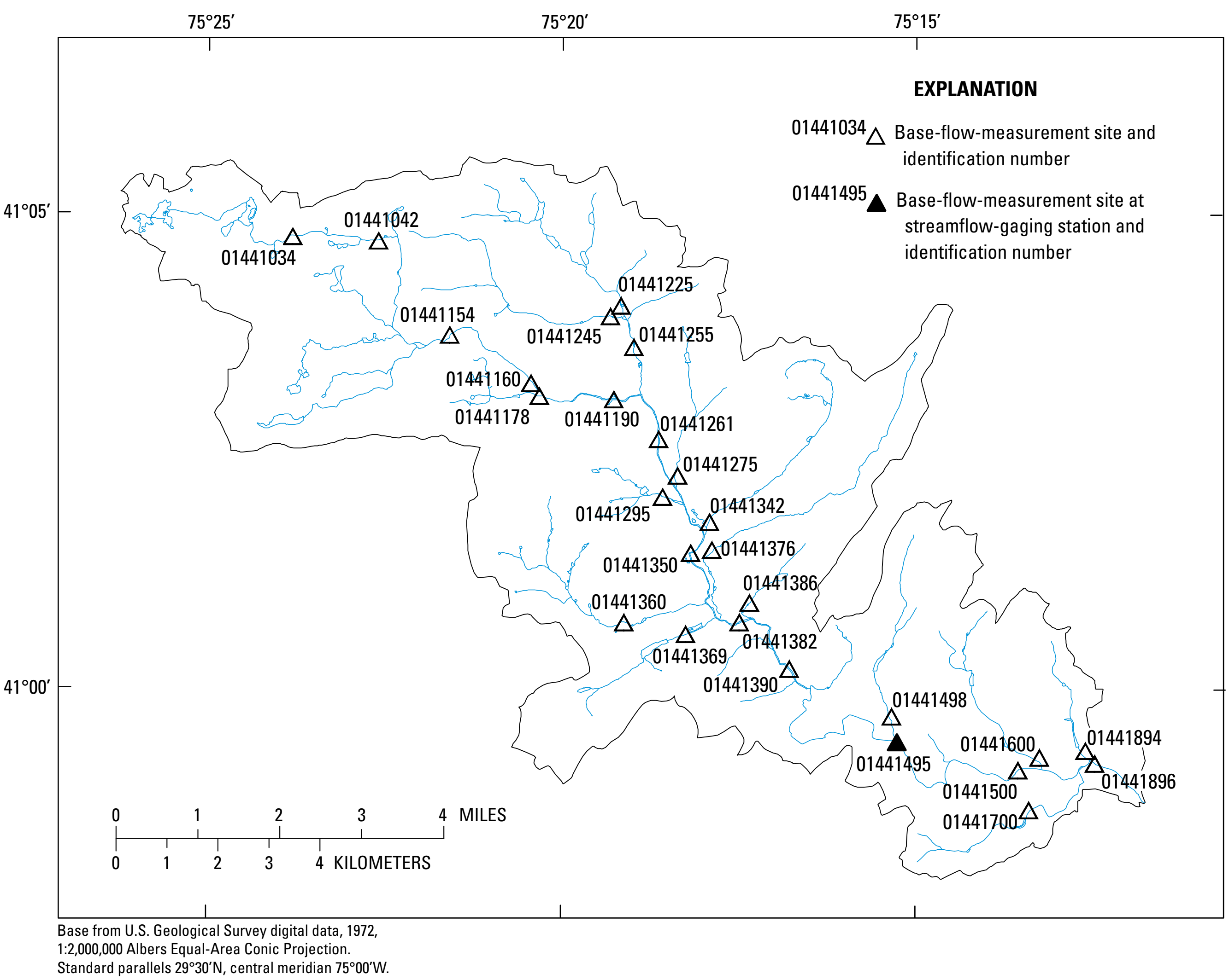


Figure 10. Base-flow-measurement sites on Pocono Creek, Monroe County, Pa., for measurements made on October 13, 2004.

01441495 and 01441500, where Pocono Creek lost 3 ft^3/s. During reconnaissance for measurement sites on September 14, 2004, Wigwam Creek lost all of its flow in this area and was dry at its confluence with Pocono Creek.

Sloto and Buxton (2005, p. 21) developed a regression equation to predict flow at the Pocono Creek streamflow-gaging station using data from the streamflow-gaging station on Brodhead Creek near Analomink. Daily base flow was estimated using the HYSEP program for 44 years of data at the Analomink station (1958-2001). Using the following equation from Sloto and Buxton (2005, p. 21) to estimate base flow at the Pocono Creek station, a base-flow-frequency curve was estimated for Pocono Creek (fig. 11):

$$Y = 0.683X^{0.975} \tag{1}$$

where

Y is flow at the streamflow-gaging station on Pocono Creek, in cubic feet per second;

and

X is flow at the streamflow-gaging station on Brodhead Creek near Analomink, in cubic feet per second.

The median (50 percent) base flow of Pocono Creek at the streamflow-gaging station was 41.8 ft^3/s. Base flow measured at the Pocono Creek streamflow-gaging during base-flow measurements made on October 13, 2004, was 61.2 ft^3/s. Therefore, the base flow at the streamflow-gaging station at the time the base-flow measurements were made was 46 percent higher than the estimated median base flow.

Effect of Land-Use Changes and Ground-Water Withdrawals on Stream Base Flow

The effect of reduced recharge from land-use changes and ground-water withdrawals on stream base flow was evaluated using two models. A surface-water-flow model developed by the USEPA was used to provide areal recharge values for 2000 land use and projected full buildout land-use conditions. The USGS ground-water-flow model developed for this study was used to determine the effect of reduced recharge from the change in land use between 2000 and full buildout and additional ground-water withdrawals on stream base flow.

Surface-Water-Flow Model

A surface-water-flow model was developed for the Pocono Creek watershed by the USEPA (Hantush and Kalin, 2006) to simulate recharge, surface runoff, and base flow using the Soil and Water Assessment Tool (SWAT) model program (Neitsch and others, 2002a; Neitsch and others, 2002b). The modeled area includes the Pocono Creek watershed above the streamflow-gaging station. A description of the calibration procedures and model simulations for the Pocono Creek watershed is given by Hantush and Kalin (2006). All modeling with the SWAT model was done by Hantush and Kalin (2006).

The SWAT model is a watershed-scale model developed by the U.S. Department of Agriculture to predict the impact of land-management practices on water, sediment, and agricultural-chemical yields in large, complex watersheds with varying soils, land use, and management conditions over long periods of time. SWAT considers the following hydrologic components in model simulations: canopy storage, infiltration, soil-moisture redistribution, evapotranspiration, lateral subsurface flow, snow melting, base flow, surface runoff, ponds, transmission losses in channels, and flood routing.

The SWAT model is a physically based, spatially distributed, continuous time (long-term yield) model and is not designed to simulate detailed, single-event flood routing. SWAT divides a watershed into subwatersheds. Each subwatershed is connected through a stream channel and is further subdivided into Hydrologic Response Units (HRUs). HRUs are lumped land areas within subbasins comprised of unique land cover, soil, and management combinations. Model input parameters are set at the HRU level, and HRUs are the smallest units in SWAT where parameters are allowed to vary. The modeled area was divided into 29 subwatersheds and 109 HRUs for 2000 land use (LU2000) and 130 HRUs for full buildout land use (LU2020). Even though LU2000 and LU2020 share the same soil map, the HRU distributions are different because of distinct land-use patterns. Having 130 HRUs does not mean that there are 130 soil/land-use combinations. HRUs in a subbasin all have distinct soil/land-use combinations. On the other hand, they can share the same soil and land-use type with a HRU from another subbasin.

Hantush and Kalin (2006) calibrated and validated the SWAT model for the Pocono Creek watershed at the daily time scale for the time periods July 1, 2002, to May 31, 2004, and June 1, 2004, to April 30, 2005, respectively, using the land-use pattern for 2000. For both scenarios, a warm-up period of 30 years was used to minimize the effects of unknown initial conditions, such as antecedent soil moisture and initial water-table level. For the warm-up period, atmospheric data were obtained from two nearby climate stations (Hantush and Kalin, 2006).

Hantush and Kalin (2006) used a simulation period of 20 years (2005 to 2024) with atmospheric data generated using the internal weather generator module of the SWAT model to estimate the effect of changes in land use on the hydrology of the Pocono Creek watershed. Two land-use scenarios were considered. The first scenario (LU2000) assumed the land-use pattern of 2000 was preserved over the watershed until the end of 2024. The second scenario (LU2020) assumed land use over the watershed during the 20 years of the simulation period was the full buildout land-use pattern. In both scenarios, the land-use pattern was assumed to remain the same throughout the 20-year simulation period. In other words, the land-use

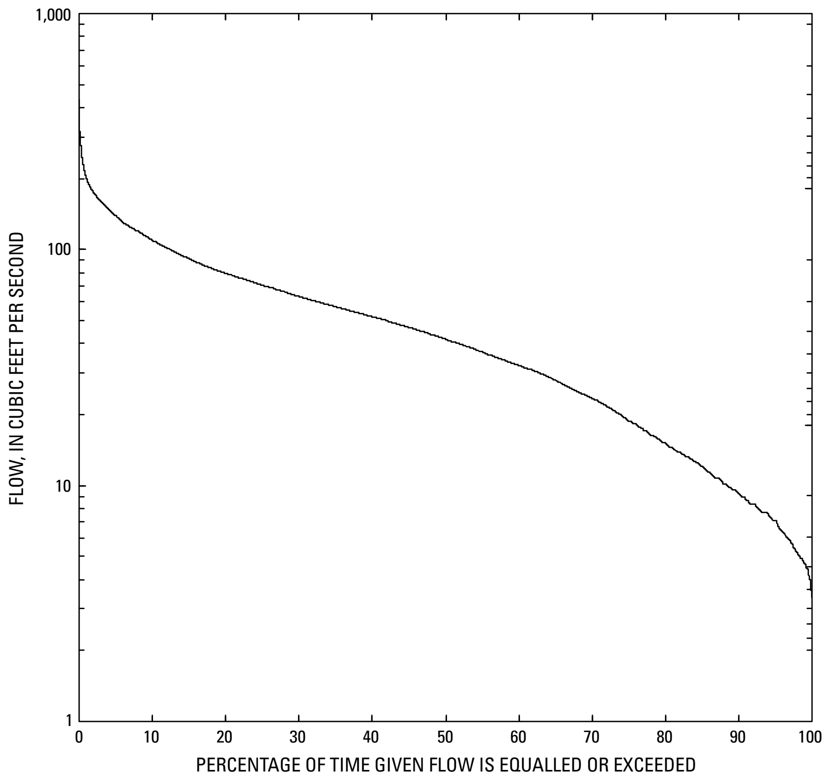


Figure 11. Cumulative estimated base-flow frequency for Pocono Creek, Monroe County, Pa.

pattern was assumed time invariant during the course of the simulations. To take into account the precipitation uncertainty, Hantush and Kalin (2006) generated 50 sets of distinct daily precipitation records 20 years long that were assumed to represent precipitation from January 1, 2005, to December 31, 2024. Measured precipitation data from 1975 to 2004 were inserted at the beginning of each record to obtain 50 precipitation input data files, each of which contained 50 years of daily precipitation. For each scenario, model simulations were performed for each of the 50 precipitation data files; thus, a total of 5,000 years of model simulations were performed at the daily time scale. The first 30 years of each realization were ignored for model warm-up, and only the last 20 years of each realization were retained for the simulations.

The SWAT model output included average streamflow, average base flow, ground-water recharge, and $Q_{7\text{-}10}$, among others (Hantush and Kalin, 2006). The percentage change was computed by comparing the LU2000 and LU2020 scenarios. Simulation results indicate that, on average, base flow is expected to be reduced by 30.7 percent. However, this is not expected to cause a noteworthy reduction in average streamflow because the reduction in base flow would be balanced by an increase in surface runoff. The lowest computed flow occurring once every 10 years averaged over a 7-consecutive-day period ($Q_{7\text{-}10}$) is expected to decline by 11 percent, a consequent result of base-flow reduction. The computed monthly median daily flow, which is an indicator for the sustainability of fish habitat, is expected to decline by 10 percent on average (Hantush and Kalin, 2006).

Ground-Water-Flow Model

Ground-water flow in the Pocono Creek watershed was simulated using the USGS MODFLOW 2000 finite-difference computer program (Harbaugh and others, 2000). The preconditioned conjugate gradient method of Hill (1990) was used to solve the model equations. The stream-aquifer package of Prudic (1989) was used to simulate stream-aquifer relations. The Groundwater Modeling System (GMS) was used as the user interface to the MODFLOW 2000 program (Environmental Modeling Systems, Inc., 2005).

Model Description and Assumptions

The model structure is based on a simplified conceptualization of the ground-water-flow system. The fractured-rock formations in the Pocono Creek watershed were modeled as equivalent porous media. Thus, it is assumed ground-water flow can be described by a flow equation based on Darcy's law. In this approach, the hydraulic conductivities used in the model represent the bulk properties of the fractured-rock formations. Water flux, which may pass through only a small fraction of the rock mass occupied by fractures, is simulated as distributed throughout the formation. The model does not simulate ground-water flow controlled by a few discrete permeable fractures or fracture zones. The model is assumed to approximately represent regional flow conditions controlled by a large number of fractures or fracture zones distributed throughout the watershed.

The modeled area included the entire Pocono Creek watershed. The lateral model boundary was the surface-water divide of Pocono Creek on all sides. It was assumed ground-water and surface-water divides coincided and no flow crossed the divides. Lateral boundaries of the model were defined as zero flux (no flow) cells at topographic divides that were assumed to be no-flow boundaries. The bottom of the model was defined as a no-flow boundary 500 ft below top of bedrock based on an analysis that showed few water-bearing zones below that depth. The top of the model was defined as a constant-flux boundary where the flux equaled the recharge rate.

Horizontally, the modeled area was divided into a 53 by 155 cell grid totaling 8,215 cells (fig. 12). Within this grid were 6,060 active cells defining the modeled area. Cell size was 500 ft by 500 ft. Land-surface elevations were taken from USGS digital elevation models (DEMs). The average land-surface elevation from the DEMs was assigned to each cell. The surface elevation of each cell was used to determine the elevation of the top of each model layer.

The bedrock geology (fig. 4) was brought into the model as a spatial data set. The surficial geology (fig. 5) was simplified and brought into the model as a spatial data set. In the model, the surficial geologic units were grouped into six categories: (1) moraine deposits, (2) ice-contact stratified drift, (3) lake deposits, (4) outwash, (5) swamp deposits, and (6) undifferentiated deposits.

Vertically, the modeled area was discretized into four layers. Layers 1 and 2 represented the unconsolidated surficial deposits where they are present and the upper 10 ft of bedrock where the surficial deposits are absent. Depth to bedrock for 568 wells was taken from Pennsylvania Geological Survey Water Well Completion Reports. An inverse distance weighted (IDW) interpolation was used to create a depth to bedrock map for the watershed (fig. 13). The average thickness of the surficial deposits was estimated for each model cell from this map. A minimum thickness of 10 ft was used for the surficial deposits, where present. The thickness of layer 1 was set at the estimated thickness of the surficial deposits minus 5 ft. Layer 2 was assumed to be 5 ft thick everywhere. Layer 2 represents a lower conductivity unit between the upper surficial deposits and bedrock where the surficial deposits are present. Bedrock-layer thickness was based on an analysis of depth of water-bearing zones penetrated by wells, which indicated that 62 percent of water-bearing zones were penetrated within 200 ft of land surface. The analysis also indicated that few water-bearing zones were penetrated below 500 ft. Layer 3 represented shallow bedrock where water generally is under unconfined conditions and was 200 ft thick. Layer 4 represented deep bedrock where water generally is under confined conditions and was 300 ft thick.

Streams were represented by constant-head cells connected to layer 1 by a vertical conductance representing streambed properties. The location of streams was from a spatial data set. A total of 873 cells were defined as stream cells (fig. 12). The elevation of the stream bottom at each stream cell was set at 1 ft below the average land-surface elevation for the cell. The elevation of some stream bottoms was adjusted so that they were lower than the adjacent upstream cells. Streambed thickness was set at 1 ft. Stream stage was set at land surface, 1 ft above the top of the streambed. Streambed conductance was initially estimated at 1,500 ft^2/d for all stream cells and then adjusted during calibration. The final streambed conductance ranged from 5 to 3,000 ft^2/d; most streambed conductances (79 percent) were 1,500 ft^2/d.

Aquifer Hydraulic Conductivity

Hydraulic conductivity for the bedrock geologic units was determined from specific-capacity data calculated from aquifer-test data taken from Pennsylvania Geological Survey Water Well Completion Reports and the USGS Ground Water Site Inventory (GWSI) database (table 4). Specific capacity was computed from short-term (usually 2 hours or less) aquifer tests. Nearly all wells used in the analysis are domestic wells. Median specific capacities ranged from 0.08 (gal/min)/ft for the Towamensing Formation to 0.32 (gal/min)/ft for the Packerton Member of the Catskill Formation.

Initial transmissivity values for each geologic unit were calculated from reported specific-capacity data (table 4) using the method of Theis (1963, p. 332-341):

$$T' = 0.134\ Q/s\ (k - 264 \log_{10} 5\ S + 264 \log_{10} t) \qquad (2)$$

and

$$k = -66 - 264 \log_{10} (3.73\ r^2 \times 10^{-6}) \qquad (3)$$

where

- T' is estimated transmissivity, in feet squared per day;
- Q/s is specific capacity, in gallons per minute per foot;
- k is a constant;
- S is storage (dimensionless);
- t is duration of pumping, in days;

and

- r is well radius, in feet.

Because the wells used for analysis have small diameters (6 in.) and tap consolidated rock, r was set equal to the well radius (Theis, 1963, p. 335). A storage value of 0.01 was used. Values for storage between 0.01 and 0.0001 produced small changes in estimated transmissivity. For example, estimated transmissivity for the Beaverdam Run Member ranged from

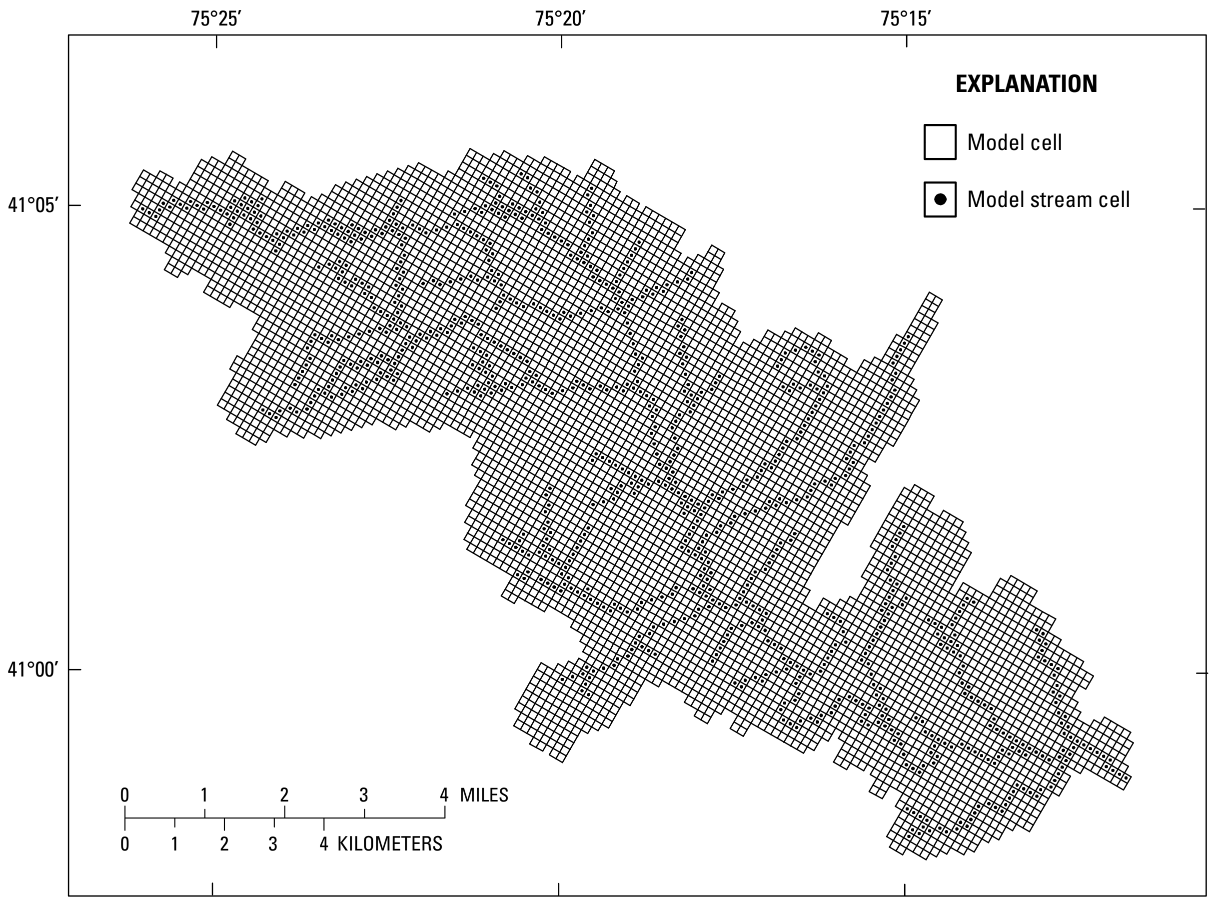


Figure 12. Model grid and stream cells for the ground-water-flow model of the Pocono Creek watershed, Monroe County, Pa.

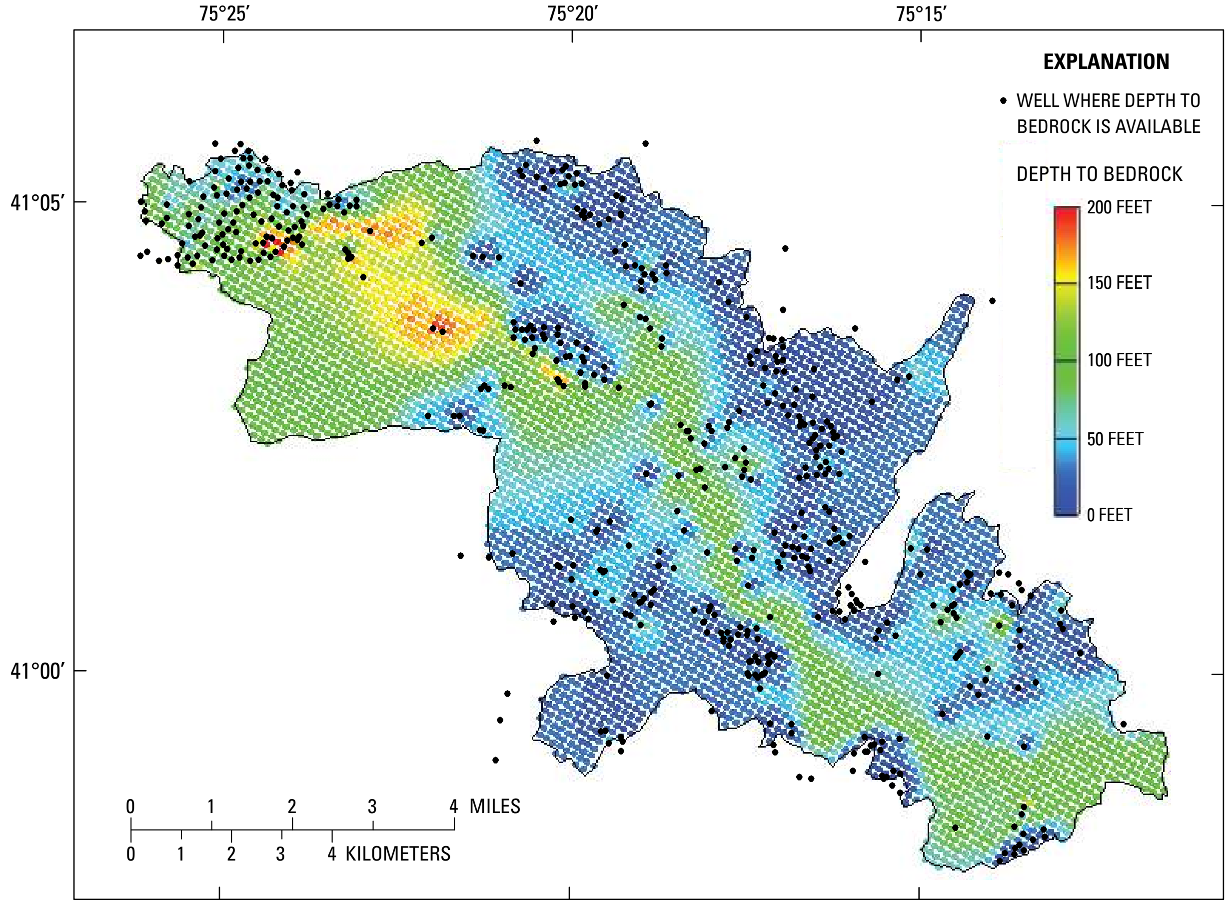


Figure 13. Estimated depth to bedrock in the Pocono Creek watershed, Monroe County, Pa.

Table 4. Specific-capacity values for bedrock units in the Pocono Creek watershed, Monroe County, Pa. Data are from Pennsylvania Geological Survey Water Well Completion Reports and the U.S. Geological Survey Ground Water Site Inventory database.

Geologic unit	Number of wells	Specific capacity (gallons per minute per foot)		Transmissivity estimated from specific capacity (feet squared per day)	
		Range	Median	Range	Median
Poplar Gap Member	103	0.16 - 7	0.25	6.5 - 2,900	102
Packerton Member	10	.12 - 1.5	.32	49 - 720	133
Long Run Member	243	.005 - 10	.14	1.9 - 4,100	56.1
Beaverdam Run Member	10	.06 - 1.5	.11	24 - 620	45.0
Walcksville Member	47	.01 - 3	.12	4.8 - 1,200	49.6
Towamensing Member	15	.02 -.25	.08	7.1 - 100	31.0
Trimmers Rock Formation	30	.01 -.62	.10	5.2 - 260	42.8
Mahantango Formation	57	.001 - 4	.09	.41 - 1,7000	38.8
Marcellus Formation	16	.01 - 9	.22	5.1 -3,800	89.4

41.2 ft^2/d for a storage value of 0.01 to 48.9 ft^2/d for a storage value of 0.0001. A monograph (Theis, 1963, p. 334) is used in the Theis method to estimate transmissivity (T) from the estimated transmissivity (T') in equation 2. Specific-capacity values on the x-axis of the monograph range from 0 to 70 (gal/min)/ft. Because the median specific-capacity values for the Pocono Creek watershed are less than 0.35 (gal/min)/ft (table 4), T was assumed to equal T'.

Initial values of hydraulic conductivity (table 5) were obtained by dividing the estimated transmissivity (table 4) by 500 ft (aquifer thickness) for layers 3 and 4 and for layers 1 and 2 where surficial deposits are absent. The initial hydraulic conductivity of each geologic unit was adjusted during model calibration (table 5). A single value of hydraulic conductivity was assigned to each geologic unit. In reality, hydraulic conductivity varies greatly from place to place within each geologic unit, usually by orders of magnitude. The final hydraulic conductivity represents the adjusted regional average for that geologic unit.

Because the surficial deposits are not used as a source of water, no hydraulic data are available except for a few aquifer tests conducted at the Butz Landfill Superfund Site. At the Butz Site, slug tests on six wells completed in Woodfordian ground moraine gave a mean hydraulic conductivity of 26 ft/d (U.S. Environmental Protection Agency, 1987). Because no hydraulic data are available for most surficial geologic units in the Pocono Creek watershed, initial values were based on similar surficial units in adjacent New Jersey (Nicholson and others, 1996) (table 6). Vertical hydraulic conductivity was set to one tenth of the horizontal hydraulic conductivity (Nicholson and Watt, 1998). Initial values of hydraulic conductivity were adjusted during model calibration. Final hydraulic conductivity values are given in table 6.

During model calibration, the moraine deposits were subdivided into two sections, moraine deposits in the Pocono Plateau Section and moraine deposits in the Low Plateau Section. This division improved base-flow simulations.

Recharge Rates

The areal distribution of recharge for model calibration was taken from the SWAT model of Hantush and Kalin (2006) for 2000 land-use conditions. Each of the 29 subwatersheds in the SWAT model had a different recharge rate; recharge rates for 2000 land-use conditions ranged from 6.11 to 22.66 in/yr. The subwatersheds and their associated recharge rates were brought into the ground-water-flow model as a spatial data set. Recharge areas (fig. 14) corresponding to the subwatersheds were created, and recharge rates from the subwatersheds (table 7) were assigned to the cells in each area. The SWAT model did not include the area between the streamflow-gaging station and the mouth of the Pocono Creek. Recharge for this area was estimated using the mean area-weighted recharge for the area above the streamflow-gaging station.

Recharge for 2000 land-use conditions from the SWAT model of Hantush and Kalin (2006) produced a volume of 4.65 × 10^6 ft^3 of base flow at streamflow-measurement site 01441896 near the mouth of Pocono Creek. The ground-water model was calibrated to base-flow data collected on October 13, 2004, when the measured volume of base flow at streamflow-measurement site 01441896 was 5.5 × 10^6 ft^3 ± 5 percent error. Therefore, the 2000 land-use recharge rates in table 7 were multiplied by 1.18 so that the volume of ground-water recharge was equal to the volume of base flow measured at streamflow-measurement site 01441896 on October 13, 2004. Recharge rates used in the model are given in table 7.

Table 5. Hydraulic conductivity values for bedrock units used in the ground-water-flow model of the Pocono Creek watershed, Monroe County, Pa.

Geologic unit	Initial hydraulic conductivity (feet per day)	Final hydraulic conductivity (feet per day)	
	Layers 1-4	Layers 1-3	Layer 4
Poplar Gap Member	0.20	0.26	0.13
Packerton Member	.27	.06	.03
Long Run Member	.11	.32	.16
Beaverdam Run Member	.09	.03	.015
Walcksville Member	.10	.3	.15
Towamensing Member	.06	.1	.05
Trimmers Rock Formation	.09	.16	.08
Mahantango Formation	.08	.3	.15
Marcellus Formation	.18	.05	.025

Pumping Rates

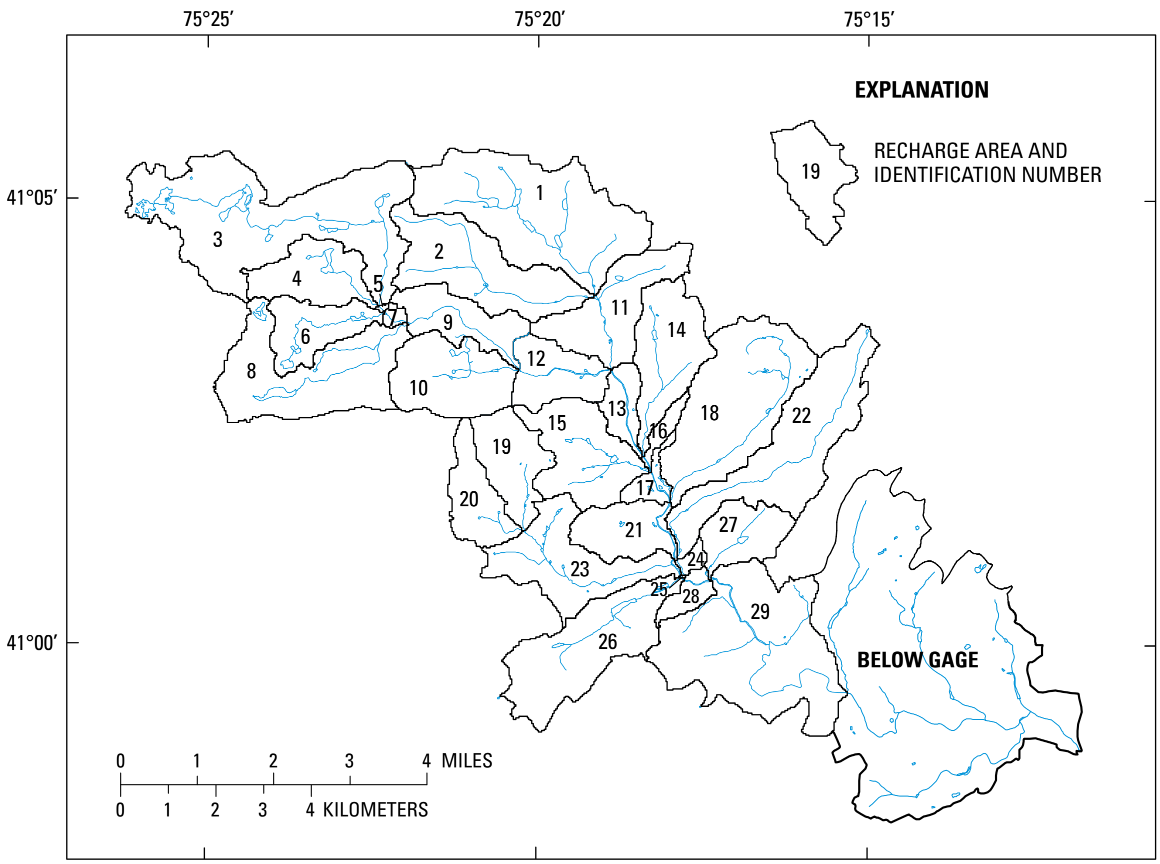
Most of the water supply in the Pocono Creek watershed is from onsite wells, and wastewater is disposed through onsite septic systems. The model included pumping from major commercial and public-supply wells (fig. 15); annual pumpage rates ranged from 0.04 to 400 Mgal/yr (table 8). The most recent pumpage data available from the DRBC, Pennsylvania Department of Environmental Protection, and the Monroe County Planning Commission were used. All pumpage is from open-hole wells in bedrock units. Data on the depth and yield of water-bearing zones in the wells were not available; therefore, pumpage was divided so that 50 percent came from layer 3 and 50 percent came from layer 4.

Simulation of Base Flow

The ground-water-flow model was calibrated to match the base-flow conditions measured on October 13, 2004. During the steady-state model calibration, adjustments were made to aquifer hydraulic conductivity and streambed conductance. To measure the effect of changes in parameter values, simulated

Table 6. Hydraulic conductivity values for surficial deposits used in the ground-water-flow model of the Pocono Creek watershed, Monroe County, Pa.

Surficial geologic unit	Initial horizontal hydraulic conductivity (feet per day)		Final horizontal hydraulic conductivity (feet per day)		Initial vertical hydraulic conductivity (feet per day)		Final vertical hydraulic conductivity (feet per day)	
	Layer 1	Layer 2	Layer 1	Layer 2	Layer 1	Layer 2	Layer 1	Layer 2
Moraine (Pocono Plateau)	26	2.6	20	2.0	2.6	0.26	2.0	.20
Moraine (Low Plateau)	26	2.6	6.6	.66	2.6	.26	.66	.066
Outwash	100	10	49	4.9	10	1	4.9	.49
Ice-contact stratified drift	60	6	30	3.0	6	.6	3.0	.30
Swamp deposits	1	.1	.33	.033	.1	.01	.033	.0033
Lake-bottom deposits	1	.1	.49	.049	.1	.01	.049	.0049
Undifferentiated	60	6	30	3.0	6	.6	3.0	.3



Base from U.S. Geological Survey digital data, 1972,
1:2,000,000 Albers Equal-Area Conic Projection.
Standard parallels 29°30′N, central meridian 75°00′W.

Figure 14. Recharge areas used in models of the Pocono Creek watershed, Monroe County, Pa. Recharge rates are given in table 7.

Table 7. Recharge rates used in the ground-water-flow model of the Pocono Creek watershed, Monroe County, Pa. Recharge areas are shown on figure 14.

Recharge area	Recharge rate used for calibration to base flow on October 13, 2004 (inches per year)	Recharge for 2000 land use[1] (inches per year)	Recharge for full buildout land use[1] (inches per year)	Change in recharge from 2000 to full buildout (percent)
1	21.59	18.26	12.00	-34.3
2	7.22	6.11	4.85	-20.5
3	16.37	13.84	10.80	-22.0
4	19.51	16.50	8.92	-45.9
5	18.67	15.79	9.52	-39.7
6	12.32	10.42	10.25	-1.6
7	13.74	11.62	16.02	37.8
8	13.70	11.59	7.10	-38.8
9	9.53	8.06	8.69	7.8
10	19.40	16.40	8.48	-48.3
11	18.58	15.71	15.89	1.1
12	11.13	9.42	9.12	-3.1
13	22.27	18.84	11.83	-37.2
14	17.74	15.00	6.87	-54.2
15	23.04	19.48	11.95	-38.7
16	21.15	17.89	7.01	-60.8
17	22.21	18.79	9.57	-49.1
18	22.58	19.09	7.85	-58.9
19	19.42	16.42	8.88	-46.0
20	21.93	18.55	10.94	-41.0
21	22.54	19.06	11.29	-40.7
22	22.93	19.39	9.31	-52.0
23	20.66	17.47	10.60	-39.3
24	22.66	19.16	11.36	-40.7
25	23.49	19.86	11.76	-40.8
26	20.47	17.31	9.11	-47.4
27	23.85	20.17	8.35	-58.6
28	26.80	22.66	16.22	-28.4
29	18.99	16.06	10.38	-35.4
Below gage	18.61	15.74	10.44	-33.7

[1] Recharge rates taken from Hantush and Kalin (2006).

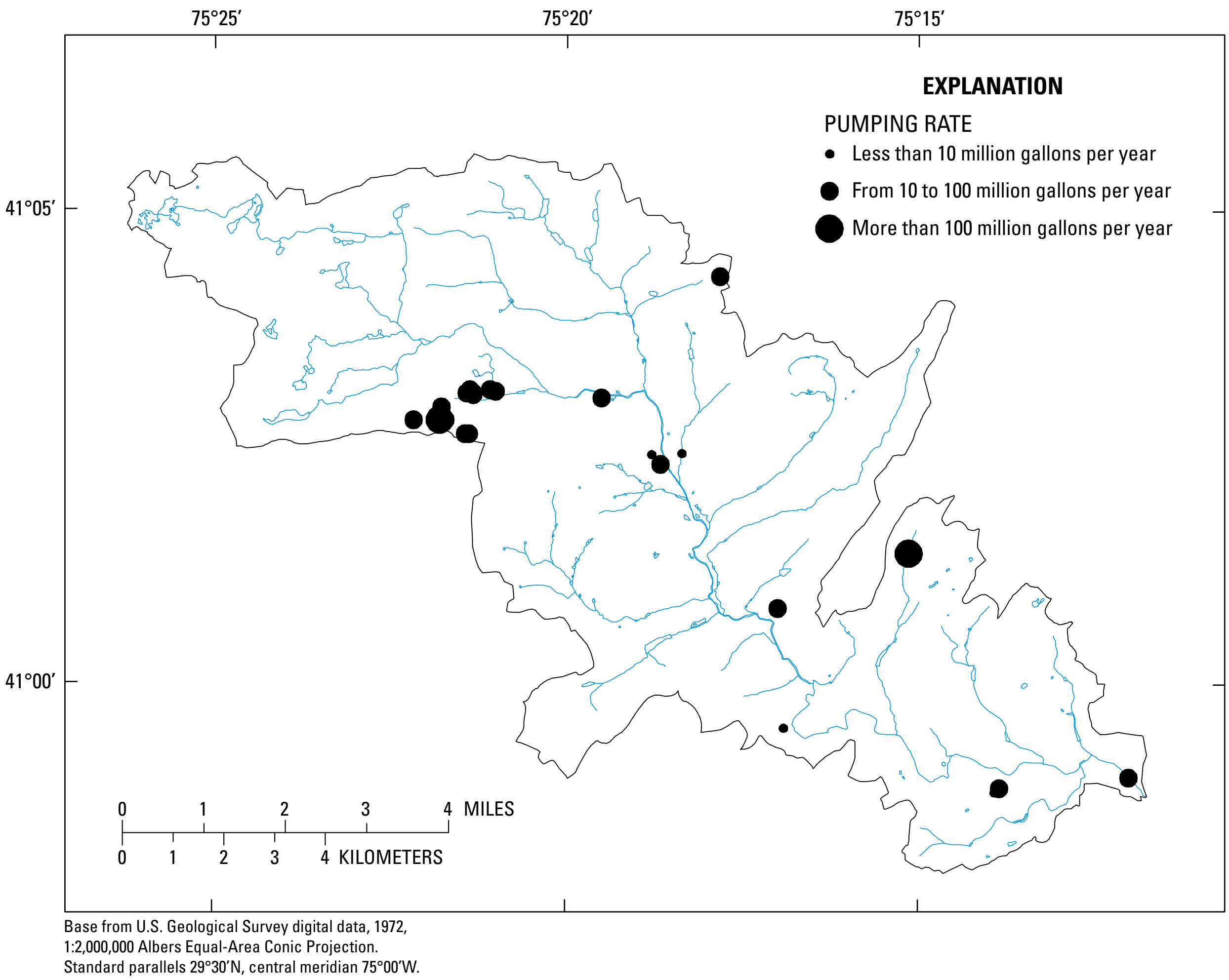


Figure 15. Ground-water pumping rates in the Pocono Creek watershed, Monroe County, Pa. Based on most recent pumpage data available from the Delaware River Basin Commission, Pennsylvania Department of Environmental Protection, and the Monroe County Planning Commission.

Table 8. Pumping rates used in the ground-water-flow model of the Pocono Creek watershed, Monroe County, Pa. All pumpage is from bedrock units and was divided so that 50 percent came from model layer 3 and 50 percent came from layer 4.

[Mgal/yr, million gallons per year]

Model row	Model column	Annual pumpage (Mgal/yr)	Owner
44	54	5.8	Camelback well 1
44	54	5.8	Camelback well 2
44	54	5.8	Camelback well 3
44	54	5.8	Camelback well 7
44	53	5.8	Camelback well 4
48	56	5.8	Camelback well 5
42	56	5.8	Camelback well 6
49	56	5.8	Camelback well 8
42	57	5.8	Camelback well 9
43	53	5.8	Camelback well 10
47	52	97	Camelback village well1
48	53	2	Camelback village well 2
49	52	150	Camelback village well 3
50	49	99	Camelback village well 4
33	113	400	Penn Estates Utilities well 5
39	78	.43	Jiffy Printing
40	80	2.6	Blue Bay
55	139	.08	Pocono Truss
55	139	.04	Bennison Wood Products
37	82	.12	Wrights Cabinet Shop
61	111	.36	Pocono Creek Park
54	139	19	Banner Metals
44	153	2.3	Beaufab Mills
48	102	37	Barton Court Mobile Home Park
15	74	17	Maple Rock Trailer Court
35	69	35	Mountain View Village

base flows were compared to measured base flows and simulated hydraulic heads were compared to measured hydraulic heads using the root mean squared error (RMSE) between measured and simulated values. The RMSE is calculated by

$$\mathrm{RMSE} = \sqrt{\sum (v_m - v_s)^2 / n} \tag{4}$$

where

v_m is the measured value,

v_s is simulated value,

and

n is number of measurement sites.

The RMSE for base flow of the calibrated model is 4.7 ft^3/s.

A comparison between measured and simulated base flows is shown in figure 16. In general, flows less than 10 ft^3/s and greater than 45 ft^3/s compare well. Simulated flows between 10 ft^3/s and 45 ft^3/s are less than measured flows. These stations are on Pocono Creek east of Camelback Mountain and on the main stem of Pocono Creek above the streamflow-gaging station. Measured base flow ranged from 0.14 to 2.1 $(ft^3/s)/mi^2$; the average was 1.23 $(ft^3/s)/mi^2$. Simulated base flow ranged from 0.03 to 2.29 $(ft^3/s)/mi^2$; the average was 1.23 $(ft^3/s)/mi^2$.

A sensitivity analysis was conducted to determine which model-input parameters had the greatest effect on simulated base flow. A sensitivity analysis is the process of varying model-input parameters over a reasonable range (the range of uncertainty in values of the model parameters) and observing the relative change in model response (base flow). The purpose of the sensitivity analysis is to demonstrate the sensitivity of the model simulations to uncertainty in values of model-input data. The sensitivity analysis was done by systematically changing the value of a single model-input parameter while holding the values of the other input variables constant. The changes in RMSE between measured and simulated base flow were compared (figs. 17 and 18). A line with little or no slope

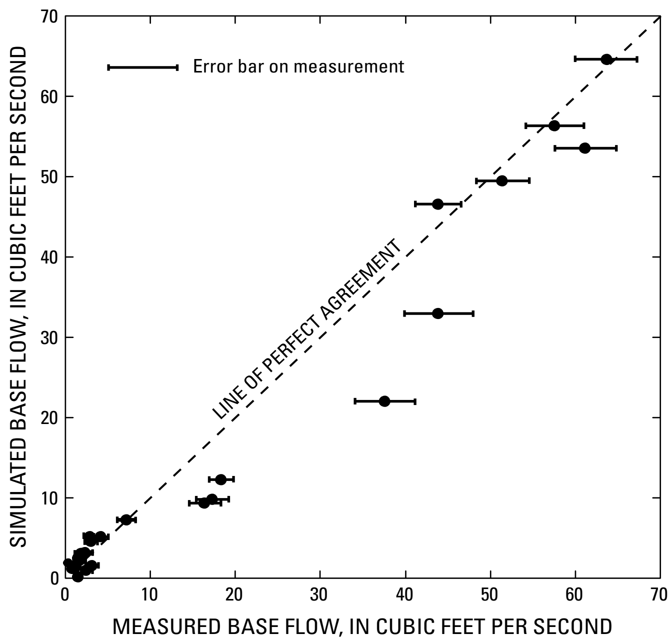


Figure 16. Relation between measured and simulated base flow of Pocono Creek watershed, Monroe County, Pa., October 13, 2004.

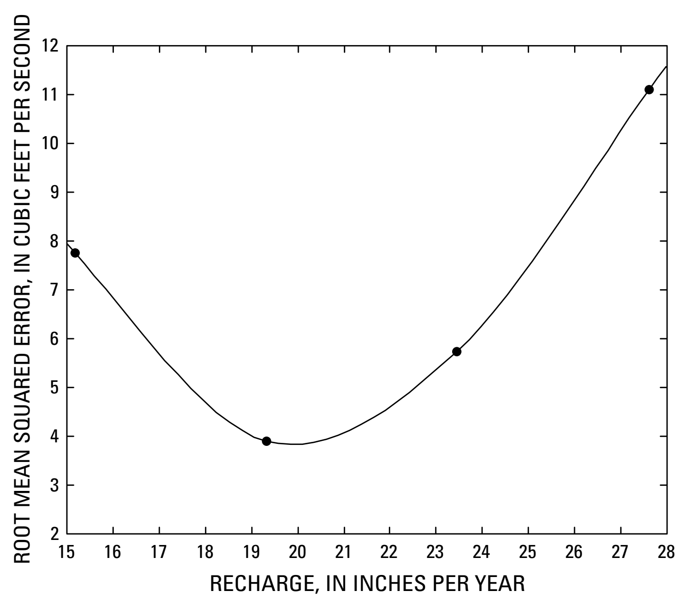


Figure 17. Effect of varying the recharge rate on the root mean squared error between measured and simulated base flow in the Pocono Creek watershed, Monroe County, Pa.

on figures 17 and 18 indicates little sensitivity of the model output to changes in the value of the input parameter. A line with a steep slope indicates greater sensitivity of the model output to changes in the value of the input parameter.

Over the range of values tested, the sensitivity analysis showed base flow was most sensitive to changes in recharge (fig. 17). Base flow was less sensitive to changes in the values of the horizontal hydraulic conductivity of the surficial geologic units and streambed conductance and relatively insensitive to changes in the value of the vertical hydraulic conductivity of the surficial geologic units and the hydraulic conductivity of the bedrock units (fig. 18).

Simulation of Hydraulic Head

In addition to measuring base flow in the watershed on October 13, 2004, water levels were measured in 15 wells (fig. 2). After calibrating the model to base flow, hydraulic conductivity was further adjusted to calibrate the model to hydraulic head (fig. 19). The measured hydraulic heads were then compared to simulated heads. The mean difference between measured and simulated heads in the 15 wells was 15 ft. Differences ranged from -56 to 78 ft. The RMSE between measured and simulated heads was 35 ft.

A sensitivity analysis was conducted to determine which model-input parameters had the greatest effect on simulated hydraulic head. Over the range of values tested, the sensitivity analysis showed hydraulic head was most sensitive to changes in the hydraulic conductivity of the bedrock (fig. 20). Hydraulic head was less sensitive to changes in the values of

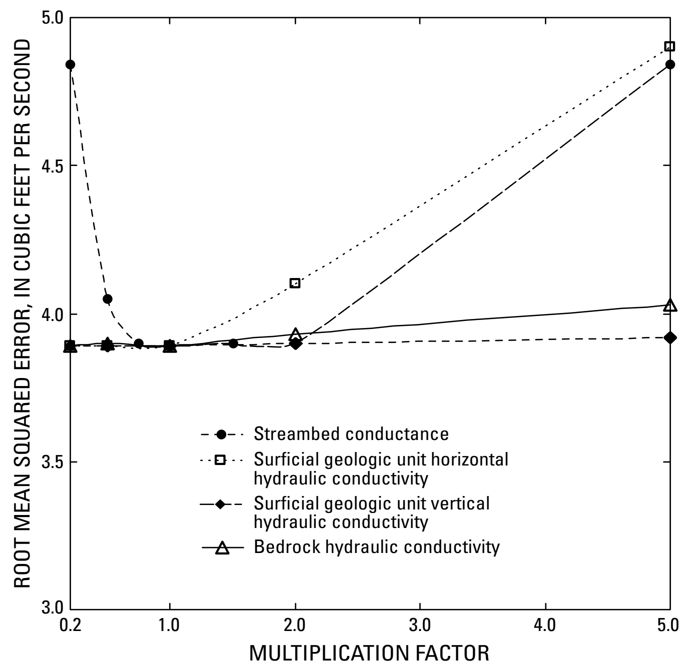


Figure 18. Effect of varying the value of hydraulic conductivity on the root mean squared error between measured and simulated base flow of Pocono Creek watershed, Monroe County, Pa., October 13, 2004.

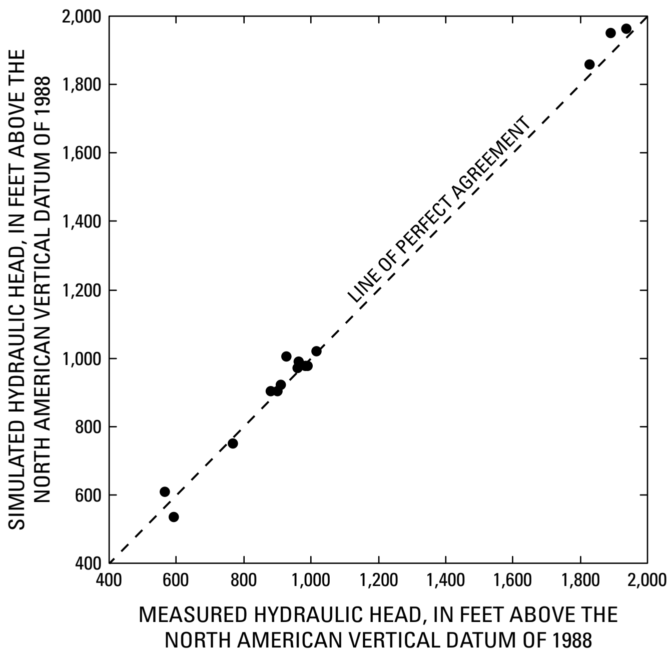


Figure 19. Relation between measured and simulated hydraulic head in the Pocono Creek watershed, Monroe County, Pa., October 13, 2004.

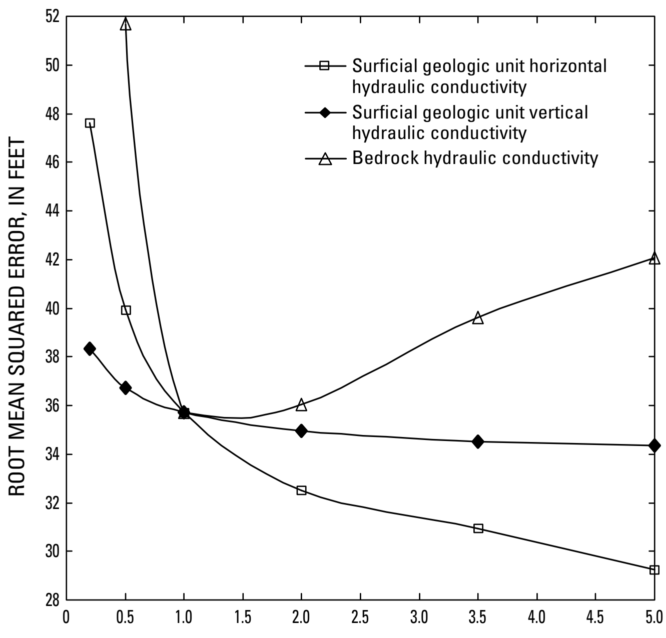


Figure 20. Effect of varying the value of hydraulic conductivity on the root mean squared error between measured and simulated hydraulic head in the Pocono Creek watershed, Monroe County, Pa.

the horizontal hydraulic conductivity of the surficial geologic units and recharge (fig. 21) and least sensitive to changes in the value of the vertical hydraulic conductivity of the surficial geologic units (fig. 20).

Differences between measured and simulated heads result from (1) the use of a single hydraulic conductivity for an areally extensive geologic unit where hydraulic conductivity ranges over several orders of magnitude, (2) comparison of head averaged over the area of a cell with a point measurement, and (3) substantial topographic relief in some cells. Simulated heads represent the average head in the model cell; the measured head represents a point measurement somewhere within the model cell. The change in land-surface elevations over the area of some cells is substantial. The high topographic relief likely results in relatively steep vertical and horizontal gradients, and the model grid size in these areas probably leads to a large inequity between measured and simulated heads.

Model Limitations

Numerical models of ground-water flow are limited in their representation of the physical system because they contain many simplifications and assumptions. Results from ground-water-flow models have a degree of uncertainty primarily because detailed three-dimensional distributions of aquifer parameters are rarely, if ever, available. Limitations exist in ground-water-flow models because of the difficulties inherent in the interpretation and representation of the complex geometry and spatial variability of the hydrogeologic materials and geologic structures in the hydrogeologic

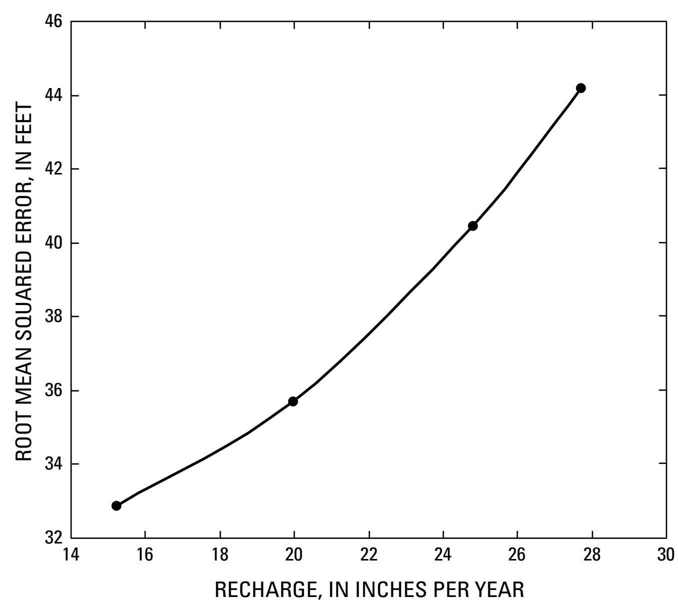


Figure 21. Effect of varying the recharge rate on the root mean squared error between measured and simulated hydraulic head in the Pocono Creek watershed, Monroe County, Pa.

framework. Another limitation is that model calibration yields non-unique sets of parameter estimates because different combinations of hydrogeologic conditions may lead to similar observations of base flows and hydraulic heads. Although the ground-water-flow model presented in this report provides a relatively good fit between simulated and measured values, the model is subject to limitations. These limitations, discussed in the following paragraphs, should be taken into consideration when using the model or evaluating model results.

Although a ground-water-flow model can be a useful tool for investigating stream-aquifer interactions, it is a simplified approximation of the actual system and is based on average or estimated conditions. The accuracy of model predictions are dependent on the availability and accuracy of the input data used for model calibration. Calibration for this model was based on one set of base-flow and water-level measurements. Model calibration results were assumed to be representative of long-term, steady-state conditions. Model calibration could be improved if several or larger sets of base-flow and water-level measurements were available; a larger set of water-level data may have led to a more robust simulation of hydraulic conductivity values.

In general, the scale of this model and the level of detail are intended for analysis on a basin-wide scale. Although this model might be useful for smaller-scale investigations, it lacks sufficient details for direct application to small-scale (site) investigations. Characterization of fractured-rock aquifers is difficult because measurements of hydraulic properties are local and sparse, permeability varies by orders of magnitude over short distances, and the three-dimensional configuration of transmissive fractures and fracture zones is complex. In the model, a single value of hydraulic conductivity is assigned to each geologic unit. Therefore, the model may not closely reproduce drawdowns from a local aquifer test because the assigned regional hydraulic conductivity may differ considerably from the hydraulic conductivity at a given pumped well.

The surficial geology was mapped only at the land surface. The vertical distribution and thickness of the sediments in the watershed were not mapped and are not known. In addition, the hydraulic characteristics of the surficial materials are not known. The thickness of the surficial sediments was inferred from driller-reported depths to bedrock where domestic wells were drilled. Distribution of these data points over the watershed was not uniform. Additional data on surficial-sediment thickness, vertical grain-size distribution, and hydraulic properties would improve model calibration.

The model first was calibrated to match base flows in the watershed because stream base flow was of primary interest. Only a few data points were available to compare measured and simulated heads. A potentiometric-surface map is not available for the Pocono Creek watershed. Even though base flow is reasonably well simulated, hydraulic head may not be well simulated everywhere in the modeled area.

The ground-water-flow model was used for steady-state simulations. For predictive simulations, steady-state simulations represent the maximum expected effects. Determining changes with time requires a model calibrated for transient flow. Transient calibration would require values for seasonal and possibly monthly, weekly, or even daily recharge; ground-water evapotranspiration rates; and measured water levels and base flows over a range of climatic conditions. In addition, a storativity value would be required for each geologic unit.

Effect of Land-Use Changes on Base Flow

Land use in the Pocono Creek watershed was determined by Hantush and Kalin (2006, p. 39-40) for 2000 (LU2000) and estimated for full buildout (LU2020), which was estimated to occur in 2020 or later (fig. 22). Full buildout was based on zoning and assumed that all developable land was developed in accordance with zoning in effect in 2000. Land-use percentages for 2000 and full buildout are given in table 9.

Hantush and Kalin (2006) used the SWAT model to determine recharge to the ground-water system for 2000 and full buildout land-use conditions in the Pocono Creek watershed (table 7). The change in estimated recharge in the 29 recharge areas ranged from an increase of 37.8 percent to a decrease of 60.8 percent. Recharge decreased in 26 of the 29 recharge areas. Because the SWAT model did not include the area below the streamflow-gaging station, the average percentage reduction in recharge over the watershed above the streamflow-gaging station (33.7 percent) was applied to the area below the streamflow-gaging station for the ground-water-flow model.

The ground-water-flow model was used to simulate the difference in base flow between the 2000 and full buildout land-use conditions with the recharge rates listed in table 7 using steady-state simulations. Simulated base flow decreased from 3.8 to 63 percent (table 10) at the 27 streamflow-measurement sites (fig. 9). Base flow at the streamflow-gaging station decreased 25 percent. This is in general agreement with the SWAT model, which estimated a 30.6 percent loss in base flow at the streamflow-gaging station (Hantush and Kalin, 2006, p. 42).

Effect of Additional Ground-Water Withdrawals on Base Flow

Additional ground-water withdrawals were simulated in the Scot Run and Cranberry Creek subwatersheds. To estimate the effect of additional ground-water withdrawals on base flow, two sets of steady-state simulations were run, one set using recharge for 2000 land use and one set using recharge for full buildout land use. Hypothetical wells were added to each subwatershed to simulate additional ground-water pumping. In the Scot Run subwatershed, the hypothetical wells were placed close to the stream and away from the surface-water divide between Scot Run and Transue Run. In the Cranberry Creek subwatershed, the hypothetical wells were placed away from the stream and near the surface-water divides between Cranberry Creek and the adjacent subwatersheds. Combined

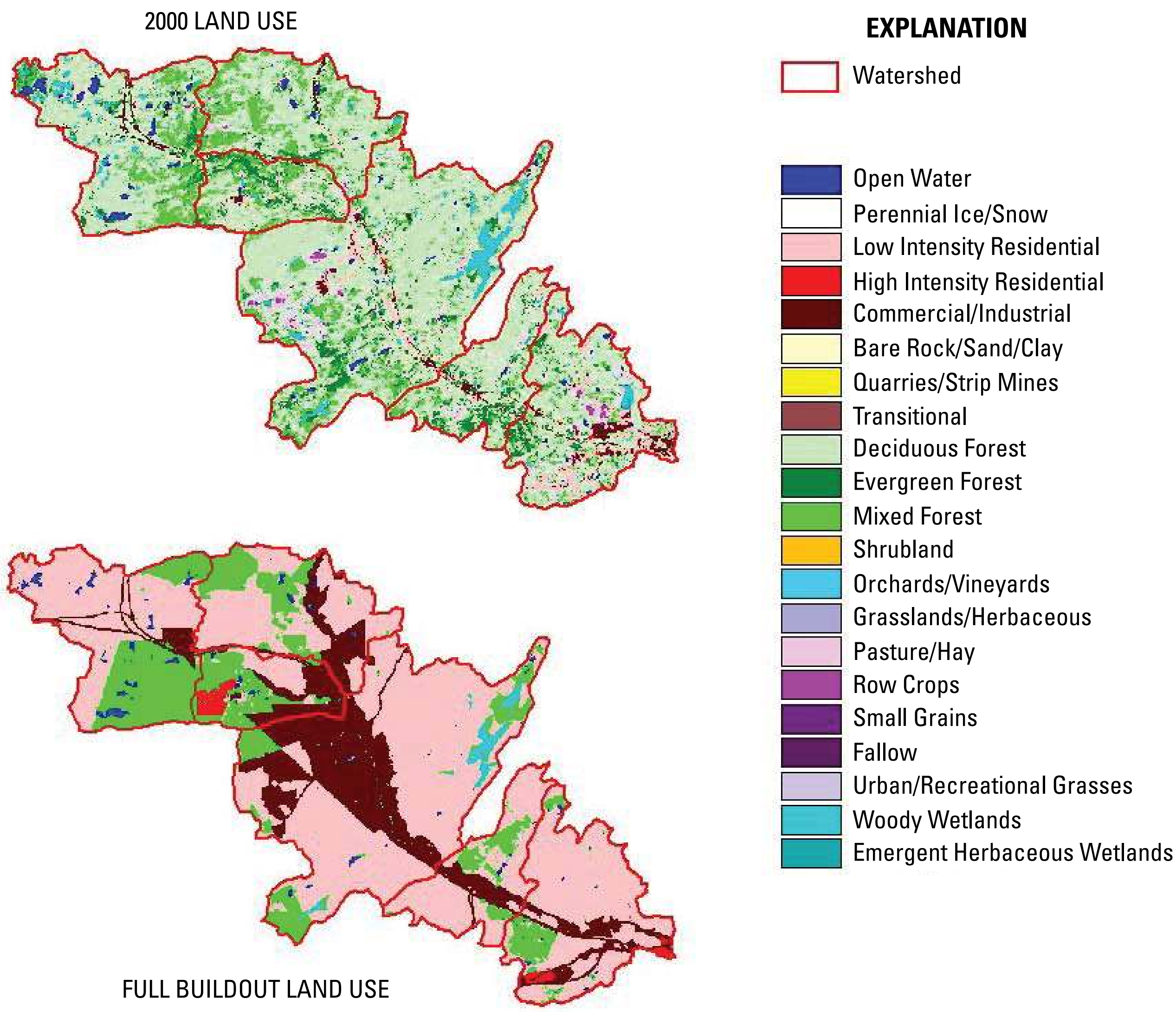


Figure 22. Land use in 2000 and projected land use for full buildout, Pocono Creek watershed, Monroe County, Pa. From Hantush and Kalin (2006, p. 40).

Table 9. Land use in 2000 and projected land use at full buildout, Pocono Creek watershed, Monroe County, Pa. From Hantush and Kalin (2006, p. 40).

Land use	2000 (percent)	Projected for full buildout (percent)
Residential - high density	0.05	0.77
Residential - medium density	0	8.00
Residential - low density	3.53	44.19
Commercial and transportation	2.25	22.84
Pasture	3.52	.27
Water	1.43	1.43
Wetlands	3.80	3.80
Forest	85.23	18.70
Agriculture row crops	.19	0

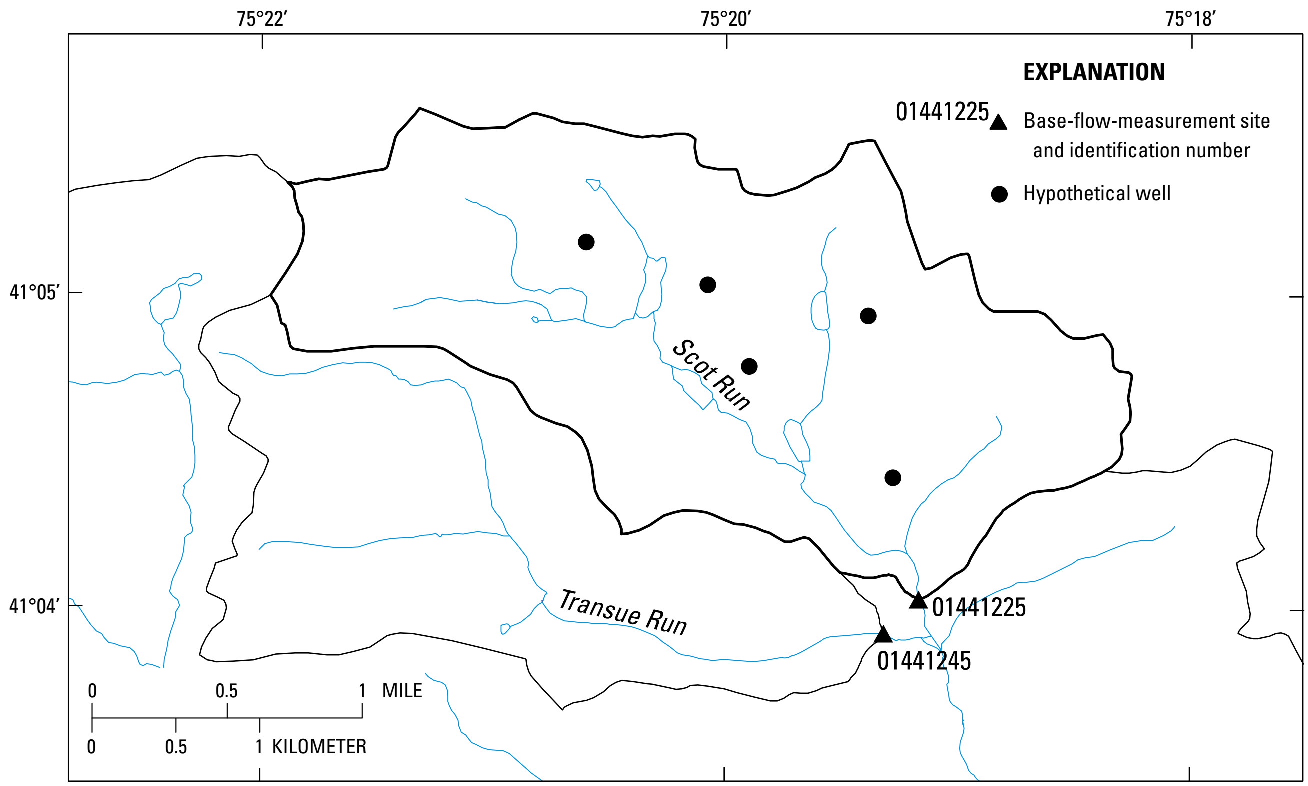
Table 10. Simulated base flow for 2000 and full buildout land-use conditions in the Pocono Creek watershed, Monroe County, Pa. Streamflow-measurement station locations are shown on figure 10.

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

Streamflow-measurement site identification number	Simulated average base flow for 2000 land use (ft^3/s)	Simulated average base flow for full buildout land use (ft^3/s)	Difference in simulated base flow (ft^3/s)	Difference in simulated base flow (percent)
01441034	1.5	1.3	-0.2	-13
01441042	1.7	1.5	.-2	-12
01441225	4.4	3.5	-.9	-20
01441245	.78	.75	-.03	-3.8
01441255	6.1	5.2	-.9	-15
01441154	7.7	7.0	-.7	-9.1
01441160	8.1	7.5	-.6	-7.4
01441178	1.3	1.1	-.2	-15
01441190	10.1	9.5	-.6	-5.9
01441261	18.5	17.0	-1.5	-8.1
01441275	.93	.35	-.6	-62
01441295	1.3	.96	-.3	-26
01441342	4.3	2.3	-2.0	-47
01441350	27.7	22.5	-5.2	-19
01441376	2.7	1.6	-1.1	-41
01441360	3.7	2.5	-1.2	-32
01441369	2.6	1.6	-1.0	-38
01441386	1.0	.37	-.63	-63
01441382	39.3	30.1	-9.2	-23
01441390	41.2	31.2	-10.0	-24
01441495	44.9	33.8	-11.1	-25
01441498	2.0	1.2	-.8	-40
01441500	47.3	35.4	-11.9	-25
01441600	2.2	1.4	-.8	36
01441700	1.2	.74	-.46	-38
01441894	1.8	1.2	-.6	-33
01441896	53.9	39.6	-14.3	-27

simulated pumpage from the wells ranged from 50,000 to 1,000,000 gal/d. Pumpage was equally divided between model layers 3 and 4. All pumpage was considered consumptive; that is, all water pumped was removed from the Pocono Creek watershed.

In the Scot Run subwatershed, five hypothetical wells were placed north of Scot Run (fig. 23). The effect of pumping these wells was evaluated at streamflow-measurement sites 01441225 (Scot Run) and 01441245 (Transue Run). Without additional ground-water withdrawals or a reduction in recharge caused by changes in land use, the simulated long-term-average base flow of Scot Run at site 01441225 was 4.4 ft^3/s. Under the 2000 recharge conditions and with an additional 1 Mgal/d of ground-water withdrawals, the simulated base flow of Scot Run decreased to 2.8 ft^3/s, a reduction of 1.6 ft^3/s (36 percent) (fig. 24). Using the full buildout recharge rate, the simulated base flow of Scot Run at site 01441225 was 3.5 ft^3/s (table 10). Adding an additional 1 Mgal/d of ground-water withdrawals further decreased the simulated base flow to 1.9 ft^3/s (fig. 24), which is a 2.5 ft^3/s (57 percent) decrease in base flow from the 2000 land-use recharge-rate base flow and a decrease of 1.6 ft^3/s (46 percent) from the full buildout recharge-rate base flow. Because of the placement of the hypothetical wells close to Scot Run and away from the surface-water divide, the base flow of adjacent Transue Run was not affected (fig. 24). Under a different pumping scenario, the results could be different.



Base from U.S. Geological Survey digital data, 1972,
1:2,000,000 Albers Equal-Area Conic Projection.
Standard parallels 29°30′N, central meridian 75°00′W.

Figure 23. Location of hypothetical wells in the Scot Run subwatershed, Monroe County, Pa.

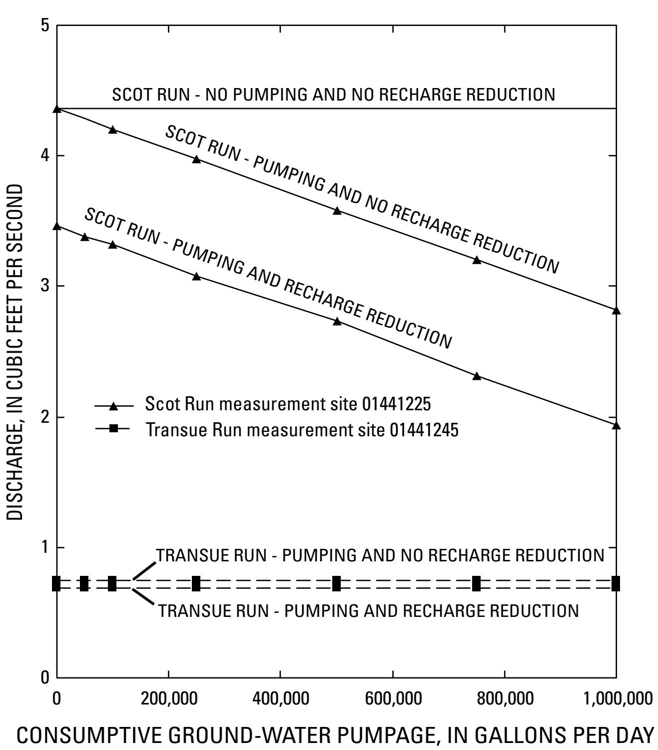


Figure 24. Change in stream base flow caused by changes in land use and consumptive ground-water withdrawals in the Scot Run subwatershed for Scot Run and Transue Run, Monroe County, Pa.

In the Cranberry Creek subwatershed, three hypothetical wells were placed close to the surface-water divide between Cranberry Creek and Bulgers Run, and three hypothetical wells were placed close to the surface-water divide between Cranberry Creek and Laurel Lake Run (fig. 25). The effect of pumping these wells was evaluated at streamflow-measurement sites 01441376 (Cranberry Creek), 01441342 (Bulgers Run), and 01441386 (Laurel Lake Run). Without additional ground-water withdrawals or a reduction in recharge caused by changes in land use, the simulated long-term-average base flow of Cranberry Creek at site 01441376 was 2.7 ft^3/s; the simulated long-term-average base flow of Bulgers Run at site 01441342 was 4.3 ft^3/s; and the simulated long-term-average base flow of Laurel Lake Run at site 01441386 was 1.0 ft^3/s.

Under the 2000 recharge conditions and with an additional 1 Mgal/d of ground-water withdrawals, the simulated base flow of Cranberry Creek decreased to 2.3 ft^3/s, a decrease of 0.4 ft^3/s (15 percent); the simulated base flow of Bulgers Run decreased to 3.7 ft^3/s, a decrease of 0.6 ft^3/s (14 percent); and the simulated base flow of Laurel Lake Run decreased to 0.5 ft^3/s, a decrease of 0.5 ft^3/s (50 percent) (fig. 26). The three hypothetical wells near the Bulgers Run surface-water divide are parallel to Bulgers Run. The three hypothetical wells near Laurel Lake Run surface-water divide are perpendicular to the headwaters of Laurel Lake Run (fig. 25). With that distribution of wells, pumping wells close to the surface-water divide in the Cranberry Creek subwatershed had the greatest effect on the base flow of Bulgers Run and the least effect on the base flow of Cranberry Creek. Under a different pumping scenario, the results could be different.

Using the full buildout recharge rate, the simulated base flow of Cranberry Creek at streamflow-measurement site 01441376 was 1.6 ft^3/s; the simulated base flow of Bulgers Run at site 01441342 was 2.3 ft^3/s; and the simulated base flow of Laurel Lake Run at site 01441386 was 0.37 ft^3/s (table 10). Adding an additional 1 Mgal/d of ground-water withdrawals in the Cranberry Creek subwatershed in the distribution shown on figure 25 further decreased the simulated base flow of Cranberry Creek to 1.0 ft^3/s (fig. 26); this was a 1.7 ft^3/s (63 percent) decrease in base flow from the 2000 land-use recharge-rate base flow and a decrease of 0.6 ft^3/s (38 percent) from the full buildout recharge-rate base flow. Adding an additional 1 Mgal/d of ground-water withdrawals in the Cranberry Creek subwatershed further decreased the simulated base flow of Bulgers Run to 1.7 ft^3/s (fig. 26); this was a 2.6 ft^3/s (60 percent) decrease in base flow from the 2000 land-use recharge-rate base flow and a decrease of 0.6 ft^3/s (26 percent) from the full buildout recharge-rate base flow. Adding an additional 1 Mgal/d of ground-water withdrawals in the Cranberry Creek subwatershed further decreased the simulated base flow of Laurel Lake Run to 0.04 ft^3/s (fig. 26); this was a 0.96 ft^3/s (96 percent) decrease in base flow from the 2000 land-use recharge-rate base flow and a decrease of 0.33 ft^3/s (89 percent) from the full buildout recharge-rate base flow. A distribution of pumping wells different than the one shown on figure 25 would result in a different distribution of base-flow decreases in the Cranberry Creek and adjacent subwatersheds.

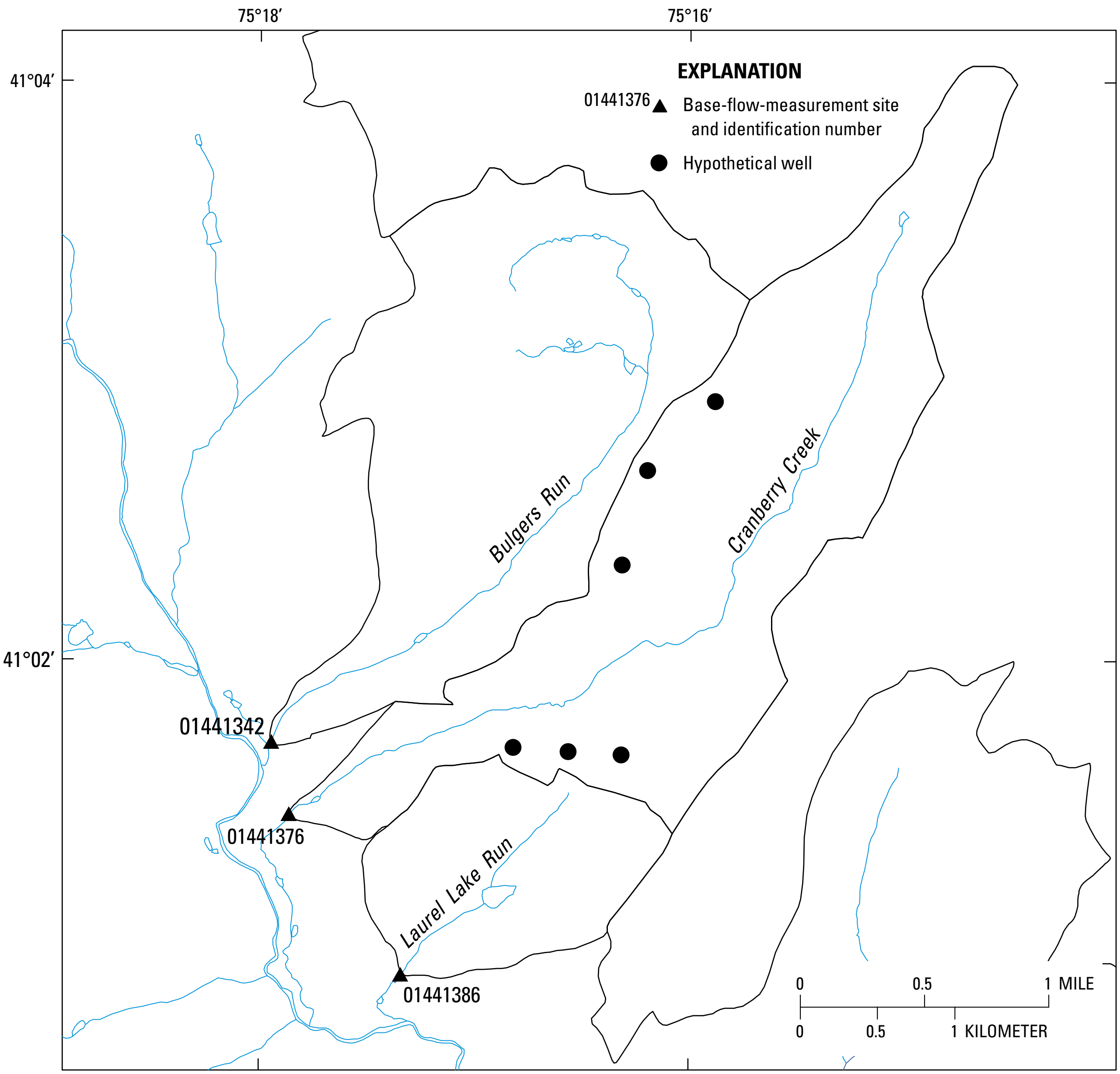
Summary and Conclusions

The Pocono Creek watershed drains 46.5 mi^2 in eastern Monroe County, one of the fastest growing counties in the Commonwealth of Pennsylvania. Between 2000 and 2020, the population of Monroe County is expected to increase by 70 percent. This population increase will result in substantial changes in land-use patterns and an increased demand for water. An evaluation of the effect of reduced recharge from land-use changes and additional ground-water withdrawals was done by the U.S. Geological Survey (USGS) in cooperation with the U.S. Environmental Protection Agency (USEPA) and the Delaware River Basin Commission as part of the USEPA's Framework for Sustainable Watershed Management Initiative. For this study, a regional numerical model of ground-water flow in the Pocono Creek watershed was developed by the USGS as a tool to evaluate interactions between the ground-water and surface-water systems. The results from the flow model were used to estimate the effects of reduced recharge caused by land-use changes and additional ground-water withdrawals on stream base flow.

The Pocono Creek watershed is underlain by sandstone, siltstone, and shale of Devonian age overlain by a veneer of glacial deposits. During the Pleistocene Epoch, continental glaciers repeatedly advanced southward from Canada and covered the Pocono Creek watershed. The last advance of ice was about 15,000 years ago. All water-supply wells in the Pocono Creek watershed are cased into and derive water from the bedrock. The unconsolidated surficial deposits are not used as a source of water. In the bedrock units, ground water moves through a network of interconnecting secondary openings—fractures and joints. Confined ground water may be present locally. In the unconsolidated surficial deposits, ground water occurs in and moves through void spaces. Water in the surficial geologic units generally is under water-table conditions.

The ground-water and surface-water systems are well connected in the Pocono Creek watershed. Base flow was measured on October 13, 2004, at 27 sites for model calibration. The measurements were made 15 days after precipitation at the end of a long base-flow recession period. The base-flow measurements show streams in the Pocono Creek watershed gained water between all sites measured except in the lower reach of Pocono Creek between two sites where Pocono Creek lost 3.4 ft^3/s. The streamflow hydrograph of Pocono Creek was separated into base-flow and surface-runoff components for the 2003-2005 calendar years. On the basis of hydrograph separations, the annual base flow of Pocono Creek made up an average of 52 percent of annual streamflow.

The effect of reduced recharge from land-use changes and additional ground-water withdrawals was evaluated using two models. A Soil and Water Assessment Tool (SWAT) model



Base from U.S. Geological Survey digital data, 1972,
1:2,000,000 Albers Equal-Area Conic Projection.
Standard parallels 29°30′N, central meridian 75°00′W.

Figure 25. Location of hypothetical wells in the Cranberry Creek subwatershed, Monroe County, Pa.

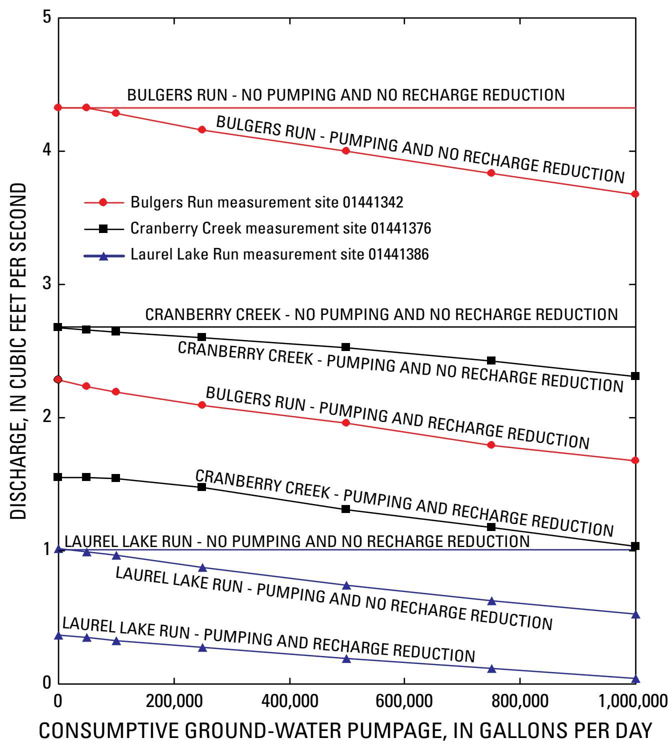


Figure 26. Change in stream base flow caused by changes in land use and consumptive ground-water withdrawals in the Cranberry Creek subwatershed for Cranberry Creek, Bulgers Run, and Laurel Lake Run, Monroe County, Pa.

developed by the USEPA was used to provide areal ground-water recharge values for 2000 land use and projected (2020) full buildout land-use conditions. The modeled area included the Pocono Creek watershed above the streamflow-gaging station. The USGS ground-water-flow model developed for this study was used to determine the effect of additional ground-water withdrawals and reduced recharge from the change in land use between 2000 and full buildout on stream base flow.

Ground-water flow in the Pocono Creek watershed was simulated using the USGS MODFLOW 2000 finite-difference computer program. The model structure was based on a simplified conceptualization of the ground-water-flow system. The fractured-rock formations in the Pocono Creek watershed were modeled as equivalent porous media. In this approach, the model is assumed to approximately represent regional flow conditions controlled by a large number of fractures or fracture zones distributed throughout the watershed. The modeled area included the entire Pocono Creek watershed. Horizontally, the modeled area was divided into a 53 by 155 cell grid with 6,060 active cells. Cell size was 500 ft by 500 ft.

The bedrock geology was brought into the model as a spatial data set. The surficial geology was simplified and also was brought into the model as a spatial data set. In the model, the surficial geologic units were grouped into six categories: (1) moraine deposits, (2) stratified drift, (3) lake deposits, (4) outwash, (5) swamp deposits, and (6) undifferentiated deposits.

Vertically, the modeled area was discretized into four layers. Layers 1 and 2 represented the unconsolidated surficial deposits where they are present and the upper 10 ft of bedrock where the surficial deposits are absent. The thickness of the surficial deposits was estimated. Layer 3 represented shallow bedrock and was 200 ft thick. Layer 4 represented deep bedrock and was 300 ft thick. A total of 873 cells represented streams. The final streambed conductance ranged from 5 to 3,000 ft^2/d; most streambed conductances (79 percent) were 1,500 ft^2/d.

Hydraulic conductivity for the bedrock units was determined from specific-capacity data calculated from aquifer-test data. The initial hydraulic conductivity of each geologic unit was adjusted during model calibration. The final hydraulic conductivity represents the adjusted regional average for that geologic unit. The surficial deposits are not used as a source of water; therefore, no hydraulic data are available except for a few aquifer tests conducted at the Butz Landfill Superfund Site. Because no hydraulic data are available for most surficial geologic units in the Pocono Creek watershed, initial values were based on values from similar surficial units in a nearby area.

The distribution of recharge rates in subwatersheds for model calibration was provided by the USEPA SWAT model for 2000 land-use conditions. Each of the 29 subwatersheds in the SWAT model had a different recharge rate; recharge rates for 2000 ranged from 6.11 to 22.66 in/yr. The subwatersheds and their associated recharge rates were brought into the ground-water-flow model as a spatial data set. Recharge areas corresponding to the subwatersheds were created, and recharge rates from the subwatersheds were assigned to the cells in each area. The SWAT model did not include the area between the streamflow-gaging station and the mouth of the Pocono Creek. Recharge for this area was estimated using the mean area-weighted recharge for the area above the streamflow-gaging station. Because the model was calibrated to base-flow data collected on October 13, 2004, the 2000 recharge rates were multiplied by 1.18 so the volume of recharge was equal to the volume of streamflow measured at the mouth of Pocono Creek. The model included pumping from major commercial and public-supply wells with annual pumpage rates ranging from 0.04 to 400 Mgal/yr. All pumpage was from bedrock units and was divided so that 50 percent came from layer 3 and 50 percent came from layer 4.

The ground-water-flow model was first calibrated to match the base-flow conditions measured on October 13, 2004. During model calibration, adjustments were made to aquifer hydraulic conductivity and streambed conductance. To calibrate the model, simulated base flows were compared to measured base flows using the root mean squared error (RMSE) between measured and simulated values; the RMSE between measured and simulated base flows of the calibrated model was 4.7 ft^3/s. After calibrating the model to base flow, hydraulic conductivity was further adjusted to calibrate the model to hydraulic head. Hydraulic heads in 15 wells also measured on October 13, 2004, were compared to simulated heads. The mean difference between measured and simulated heads was 15 ft; the RMSE between measured and simulated hydraulic heads of the calibrated model was 35 ft. The simulated base flows were most sensitive to changes in recharge, and the simulated hydraulic heads were most sensitive to changes in bedrock hydraulic conductivity.

Land use in the Pocono Creek watershed was determined for 2000 and estimated for full buildout, which was estimated to occur in 2020 or later. Full buildout was based on zoning and assumed that all developable land was developed in accordance with zoning in effect in 2000. The SWAT model was used to determine recharge to the ground-water system for 2000 and full buildout land-use conditions in the Pocono Creek watershed. The change in estimated recharge in the 29 recharge areas ranged from an increase of 37.8 percent to a decrease of 60.8 percent. Recharge decreased in 26 of the 29 recharge areas.

The USEPA SWAT model provided areal recharge values for 2000 and full buildout land-use conditions. The ground-water-flow model was used to simulate the difference in base flow between the 2000 and full buildout land-use conditions. Simulated base flow decreased from 3.8 to 63 percent at the 27 streamflow-measurement sites. Base flow at the streamflow-gaging station decreased 25 percent. This is in general agreement with the SWAT model, which estimated a 30.6 percent loss in base flow at the streamflow-gaging station.

Additional ground-water withdrawals were simulated in the Scot Run and Cranberry Creek subwatersheds for 2000 and full buildout land-use conditions. Hypothetical wells were added to each subwatershed to simulate additional ground-water pumping. In the Scot Run subwatershed, the hypothetical wells were placed close to the stream and away from the surface-water divide between Scot Run and Transue Run. In the Cranberry Creek subwatershed, the hypothetical wells were placed away from the stream and near the surface-water divides between Cranberry Creek and the adjacent subwatersheds. Combined simulated pumpage from the wells ranged from 50,000 to 1,000,000 gal/d. Pumpage was equally divided between model layers 3 and 4. All pumpage was considered consumptive; that is, all water pumped was removed from the Pocono Creek watershed.

In the Scot Run subwatershed, five hypothetical wells were placed north of Scot Run. Under the 2000 recharge conditions and with an additional 1 Mgal/d of ground-water withdrawals, the simulated base flow of Scot Run decreased 36 percent. Using the full buildout recharge rate and adding an additional 1 Mgal/d of ground-water withdrawals, simulated base flow decreased 57 percent from the 2000 land-use recharge-rate base flow and 46 percent from the full buildout recharge-rate base flow. Because of the placement of the hypothetical wells close to the Scot Run and away from the surface-water divide, the base flow of adjacent Transue Run was not affected. Under a different pumping scenario, the results could be different.

In the Cranberry Creek subwatershed, three hypothetical wells were placed close to the surface-water divide between Cranberry Creek and Bulgers Run, and three hypothetical wells were placed close to the surface-water divide between Cranberry Creek and Laurel Lake Run. Under the 2000 recharge conditions and with an additional 1 Mgal/d of ground-water withdrawals in the Cranberry Creek subwatershed, the simulated base flow of Cranberry Creek decreased 15 percent; the simulated base flow of Bulgers Run decreased 14 percent; and the simulated base flow of Laurel Lake Run decreased 50 percent. The three hypothetical wells near the Bulgers Run surface-water divide are parallel to Bulgers Run. The three hypothetical wells near Laurel Lake Run surface-water divide are perpendicular to the headwaters of Laurel Lake Run. With that distribution of wells, pumping wells close to the surface-water divide in the Cranberry Creek subwatershed had the greatest effect on the base flow of Bulgers Run and the least effect on the base flow of Cranberry Creek. Under a different pumping scenario, the results could be different.

Using the full buildout recharge rate and adding an additional 1 Mgal/d of ground-water withdrawals in the Cranberry Creek subwatershed, the simulated base flow of Cranberry Creek decreased 63 percent from the 2000 land-use recharge-rate base flow and decreased 38 percent from the full buildout recharge-rate base flow. The simulated base flow of Bulgers Run decreased 60 percent from the 2000 land-use recharge-rate base flow and decreased 26 percent from the full buildout recharge-rate base flow. The simulated base flow of Laurel lake Run decreased 96 percent from the 2000 land-use recharge-rate base flow and decreased 89 percent from the full buildout recharge-rate base flow.

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