Prepared in cooperation with the Somerset County Conservation District

Water Quality and Quantity and Simulated Surface-Water and Groundwater Flow in the Laurel Hill Creek Basin, Southwestern Pennsylvania, 1991–2007

Scientific Investigations Report 2016–5082

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

Cover: Photo of Laurel Hill Creek as it enters into Laurel Hill Lake at Laurel Hill State Park, Pennsylvania, photo taken on June 22, 2009. (Photograph provided by Daniel Galeone, U.S. Geological Survey)

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	0.4047	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
million gallons per day (Mgal/d)	3,785	cubic meter per day (m^3/d)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows: °F=(1.8×°C)+32.

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).

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25°C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

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Abstract

Laurel Hill Creek is considered one of the most pristine waterways in southwestern Pennsylvania and has high recreational value as a high-quality cold-water fishery; however, the upper parts of the basin have documented water-quality impairments. Groundwater and surface water are withdrawn for public water supply and the basin has been identified as a Critical Water Planning Area (CWPA) under the State Water Plan. The U.S. Geological Survey, in cooperation with the Somerset County Conservation District, collected data and developed modeling tools to support the assessment of water-quality and water-quantity issues for a basin designated as a CWPA. Streams, springs, and groundwater wells were sampled for water quality in 2007. Streamflows were measured concurrent with water-quality sampling at main-stem sites on Laurel Hill Creek and tributaries in 2007. Stream temperatures were monitored continuously at five main-stem sites from 2007 to 2010. Water usage in the basin was summarized for 2003 and 2009 and a Water-Analysis Screening Tool (WAST) developed for the Pennsylvania State Water Plan was implemented to determine whether the water use in the basin exceeded the "safe yield" or "*the amount of water that can be withdrawn from a water resource over a period of time without impairing the long-term utility of a water resource.*" A groundwater and surface-water flow (GSFLOW) model was developed for Laurel Hill Creek and calibrated to the measured daily streamflow from 1991 to 2007 for the streamflow-gaging station near the outlet of the basin at Ursina, Pa. The CWPA designation requires an assessment of current and future water use. The calibrated GSFLOW model can be used to assess the hydrologic effects of future changes in water use and land use in the basin.

Analyses of samples collected for surface-water quality during base-flow conditions indicate that the highest nutrient concentrations in the main stem of Laurel Hill Creek were at sites in the northeastern part of the basin where agricultural activity is prominent. All of the total nitrogen (N) and a majority of the total phosphorus (P) concentrations in the main stem exceeded regional nutrient criteria levels of 0.31 and 0.01 milligrams per liter (mg/L), respectively. The highest total N and total P concentrations in the main stem were 1.42 and 0.06 mg/L, respectively. Tributary sites with the highest nutrient concentrations are in subbasins where treated wastewater is discharged, such as Kooser Run and Lost Creek. The highest total N and total P concentrations in subbasins were 3.45 and 0.11 mg/L, respectively. Dissolved chloride and sodium concentrations were highest in the upper part of the basin downstream from Interstate 76 because of road deicing salts. The mean base-flow concentrations of dissolved chloride and sodium were 117 and 77 mg/L, respectively, in samples from the main stem just below Interstate 76, and the mean concentrations in Clear Run were 210 and 118 mg/L, compared to concentrations less than 15 mg/L in tributaries that were not affected by highway runoff. Water quality in forested tributary subbasins underlain by the Allegheny and Pottsville Formations was influenced by acidic precipitation and, to a lesser extent, the underlying geology as indicated by pH values less than 5.0 and corresponding specific conductance ranging from 26 to 288 microsiemens per centimeter at 25 degrees Celsius for some samples; in contrast, pH values for main stem sites ranged from 6.6 to 8.5. Manganese (Mn) was the only dissolved constituent in the surface-water samples that exceeded the secondary maximum contaminant level (SMCL). More than one-half the samples from the main stem had Mn concentrations exceeding the SMCL level of 50 micrograms per liter (µg/L), whereas only 19 percent of samples from tributaries exceeded the SMCL for Mn.

Stream temperatures along the main stem of Laurel Hill Creek became higher moving downstream. During the summer months of June through August, the daily mean temperatures at the five sites exceeded the limit of 18.9 degrees Celsius (°C) for a cold-water fishery. The maximum instantaneous values for each site ranged from 27.2 to 32.8 °C.

Water-quality samples collected at groundwater sites (wells and springs) indicate that wells developed within the Mauch Chunk Formation had the best water quality, whereas wells developed within the Allegheny and Pottsville Formations yielded the poorest water quality. Waters from the Mauch Chunk Formation had the highest median pH (7.6) and alkalinity (80 mg/L calcium carbonate) values. The lowest pH and alkalinity median values were in waters from the Allegheny and Pottsville Formations. Groundwater samples collected from wells in the Allegheny and Pottsville Formations also had the highest concentrations of dissolved iron (Fe) and dissolved Mn. Seventy-eight percent of the groundwater samples collected from the Allegheny Formation exceeded the SMCL of 300 µg/L for Fe and 50 µg/L for Mn. Forty-three and 62 percent of the groundwater samples collected from the Pottsville Formation exceeded the SMCL for iron and Mn, respectively. The highest Fe and Mn concentrations for surface waters were measured for tributaries draining the Pottsville Formation. The highest median Fe concentration for tributaries was in samples from streams draining the Allegheny Formation.

During base-flow conditions, the streamflow per unit area along the main stem of Laurel Hill Creek was lowest in the upper parts of the basin [farthest upstream site 0.07 cubic foot per second per square mile ($ft^3/s/mi^2$)] and highest (two sites averaging about 0.20 ($ft^3/s/mi^2$) immediately downstream from Laurel Hill Lake in the center of the basin. Tributaries with the highest streamflow per unit area were those subbasins that drain the western ridge of the Laurel Hill Creek Basin. The mean streamflow per unit area for tributaries draining areas that extend into the western ridge and draining eastern or central sections was 0.24 and 0.05 $ft^3/s/mi^2$, respectively. In general, as the drainage area increased for tributary basins, the streamflow per unit area increased.

Criteria established by the Pennsylvania Department of Environmental Protection indicate that the safe yield of water withdrawals from the Laurel Hill Creek Basin is 1.43 million gallons per day (Mgal/d). Water-use data for 2009 indicate that net (water withdrawals subtracted by water discharges) water withdrawals from groundwater and surface-water sources in the basin were approximately 1.93 Mgal/d. Water withdrawals were concentrated in the upper part of the basin with approximately 80 percent of the withdrawals occurring in the upper 36 mi^2 of the basin. Three subbasins—Allen Creek, Kooser Run, and Shafer Run— in the upper part were affected the most by water withdrawals such that safe yields were exceeded by more than 1,000 percent in the first two and more than 500 percent in the other. In the subbasin of Shafer Run, intermittent streamflow characterizes sections that historically have been perennial.

The GSFLOW model of the Laurel Hill Creek Basin is a simple one-layer representation of the groundwater flow system. The GSFLOW model was primarily calibrated to reduce the error term associated with base-flow periods. The total amount of observed streamflow at the Laurel Hill Creek at Ursina, Pa. streamflow-gaging station and the simulated streamflow were within 0.1 percent over the entire modeled period; however, annual differences between simulated and observed streamflow showed a range of -27 to 24 percent from 1992 to 2007 with nine of the years having less than a 10-percent difference. The primary source of simulated streamflow in the GSFLOW model was the subsurface (interflow; 62 percent), followed by groundwater (25 percent) and surface runoff (13 percent). Most of the simulated subsurface flow that reached the stream was in the form of slow flow as opposed to preferential (fast) interflow.

Introduction

Laurel Hill Creek drains a basin of approximately 125 square miles (mi^2) in Somerset, Fayette, and Westmoreland Counties in southwestern Pennsylvania. The basin is managed as “Special Protection Waters” by the Pennsylvania Department of Environmental Protection (PaDEP) (Commonwealth of Pennsylvania, 2009). A water body gains special protection status if it has been designated High Quality Water and (or) Exceptional Value Waters (Pennsylvania Department of Conservation and Natural Resources, 2003). The entire main stem and most tributaries of Laurel Hill Creek are classified as a High Quality Coldwater Fishery (HQ-CWF) with four Exceptional Value (EV) tributaries. Water is withdrawn from groundwater and surface-water sources to supply multiple users, including two resorts, three golf courses, a limestone quarry, and the Borough of Somerset. There is concern that water use is exceeding water availability.

The Water Resources Planning Act of 2002 (Act 220; 27 PA C.S. § 3101 et seq.) required that PaDEP update the Pennsylvania State Water Plan by 2008. One of the main objectives of this update was the identification of areas in the State where water demand exceeds the potable supply of water (PaDEP, 2006a). The State developed criteria to determine whether water demand in a basin was excessive relative to supply. In general, if water demand far exceeds supply, the basin would be designated as a Critical Water-Planning Area (CWPA). A CWPA is defined as a “significant hydrologic unit where existing or future demands exceed or threaten to exceed the safe yield of available water resources” (PaDEP, 2006b). A water-analysis screening tool (WAST) was developed by the U.S. Geological Survey (USGS), in cooperation with the PaDEP, to provide assistance to the State in the identification of CWPAs (Stuckey, 2008). The Laurel Hill Creek Basin is one of the basins in the State that was the focus for some of the initial work in updating the State Water Plan. The WAST was implemented for this work to determine whether water demand exceeded water supply in the Laurel Hill Creek Basin. This initial work under the auspices of the State Water Plan was conducted using 2003 water-use data provided by PaDEP. For the project on which this report is based, the initial WAST results were expanded upon by applying the WAST to specific subbasins, again using 2003 water-use data. The WAST also was used to determine whether water use exceeded safe yields in the basin by using water-use data compiled for 2009.

Laurel Hill Creek is in the Ohio River watershed; hence, the Ohio Regional Water Resources Committee (ORWRC), one of six Regional Water Resources Committees in Pennsylvania created as a result of Act 220 to address water issues across the entire State (PaDEP, 2009), is involved in making water planning decisions. Initial work documenting water use that exceeded safe yields in the basin based on WAST results prompted the ORWRC to accept the nomination of the Laurel Hill Creek Basin as a CWPA. Eventually, this nomination was forwarded to the statewide committee and in December 2010, the Laurel Hill Creek Basin was approved as a CWPA.

Under the context of Pennsylvania's State Water Plan, a Critical Area Resource Plan (CARP) needs to be developed for any area designated as a CWPA. According to the PaDEP (2006b), the following criteria need to be addressed in the development of a CARP:

(i) An identification of existing and future reasonable and beneficial uses.

(ii) A water availability evaluation, including a quantitative assessment of the available water resources and their relationship to the existing and future reasonable and beneficial uses.

(iii) An identification of the quantity of water available for new or increased uses of water in the foreseeable future and an identification of quantities required for future water uses associated with planned projects or developments.

(iv) An assessment of water quality issues that have a direct and substantial effect on water resource availability.

(v) A consideration of storm water and floodplain management within the critical water planning area and their impacts on water quality and quantity.

(vi) Identification of existing and potential adverse impacts on uses or conflicts among users or areas of the critical water planning area and identification of alternatives for avoiding or resolving such conflicts.

(vii) An identification of practicable supply-side and demand-side alternatives for assuring an adequate supply of water to satisfy existing and future reasonable and beneficial uses."

The focus of this study was to assess the quality and quantity of groundwater and surface-water sources in the Laurel Hill Creek Basin, assess the effects of current demands for water in the basin, and provide a tool for future water demands. For this study, conducted by the USGS in cooperation with the Somerset County Conservation District, water quality in the basin was assessed in summer and fall 2007. Two groundwater and surface-water sampling events were conducted in the basin during periods of little to no precipitation; therefore, the samples were indicative of base-flow or low-flow periods. Stream samples were collected in tributaries and along the main stem of the Laurel Hill Creek. Streamflow was measured for each surface-water sample collected. Groundwater samples were collected from springs and wells. Spring discharge was measured prior to the collection of water-quality samples from springs; static water level was measured and wells were purged prior to collecting water-quality samples from wells. Stream quality classification can also be defined by water temperature, with maximum temperature limits corresponding to protected uses for cold-water or warm-water fishes and associated aquatic life (Commonwealth of Pennsylvania, 2009). A network of stream temperature probes was operated from 2007 to 2010 along the main stem of Laurel Hill Creek in order to characterize the temperature regime, which is an important characteristic for a stream designated as a HQ-CWF.

Considering that withdrawals in the basin are taken from both groundwater and surface-water resources, it is critical to understand the interaction between the groundwater and surface-water systems. An integrated hydrologic model called GSFLOW (Groundwater and Surface-water FLOW) was developed by the USGS to simulate interactions between groundwater and surface-water resources. This model is based on the coupling of the USGS Modular Groundwater Flow Model (MODFLOW) (Harbaugh, 2005) and the USGS Precipitation-Runoff Modeling System (PRMS) (Leavesley and others, 1983). GSFLOW can be used to evaluate the effects of such factors as land-use change, climate variability, and water withdrawals on surface and subsurface flow. The model was designed to simulate the most important processes affecting groundwater and surface-water flow using a numerically efficient algorithm (Markstrom and others, 2008).

Laurel Hill Creek is considered to be one of the most pristine streams in southwest Pennsylvania, a relatively unique distinction for streams in the area, substantiated by the fact that the entire basin is designated as a HQ-CWF (Commonwealth of Pennsylvania, 2009). Native eastern brook trout are common throughout the basin, and the basin is stocked with more than 6,000 rainbow, brown, and golden trout annually, which gives the basin high recreational value. However, the pristine nature of the basin is being degraded and additional future degradation could result if plans to protect the hydrological resources of the basin are not developed and implemented. Over the last 10 years, the upper one-third of the basin was listed as impaired by PaDEP (2014) for water-quality issues. Excessive siltation, nutrients, and organic enrichment, with resulting low dissolved oxygen (DO), from grazing and crop-related agricultural activities have been identified as the causes of these impairments in the headwaters of Laurel Hill Creek (PaDEP, 2011).

On the basis of recommendations and findings from a Rivers Conservation Plan (Crouse & Company of Somerset and Kleinschmidt Group, 2005), basin stakeholders believe that groundwater and surface-water withdrawals also are causing streamflows to be lower than historic levels and that low streamflows are occurring more frequently. This viewpoint by the stakeholders was verified according to criteria established by the Pennsylvania Water Resources Act 220 State Water Plan, which indicates that water use in the basin far exceeds the safe yield for water withdrawals. Furthermore, low streamflows during the growing season could increase the potential for stream water warming, exacerbate the accumulation of fine sediment (siltation), and accelerate eutrophication and organic enrichment that result from excessive nutrients. Future development in the basin is likely (Mackin Engineering Company, 2010); therefore, planning is critical at this time to reduce the potential for further decline in the viability of the basin as an aquatic resource for both humans and wildlife.

Purpose and Scope

The purpose of this report is to document water-quality and water-quantity conditions for surface water and groundwater in the Laurel Hill Creek Basin during 1991–2007 as a framework for a water-resource management plan for an area designated as a Critical Water Planning Area within the context of the Pennsylvania State Water Plan. A GSFLOW model was developed for the basin as a tool to determine how future changes in water use and land use could affect the water availability for both human consumption and aquatic resources.

In general, this report

- documents the groundwater and surface-water quality and quantity in Laurel Hill Creek Basin;
- verifies existing water-use data for the basin and determines whether the quantity of water in the basin is stressed, based on the use of the WAST; and
- presents a discussion of the development, documentation, and interpretation of a surface-water and groundwater interaction model for the basin.

Results of the model improve the understanding of the relation between surface water and groundwater in the basin and the future effects of projected water use.

Study Area

The Laurel Hill Creek Basin is in the Allegheny Mountain Section of the Appalachian Plateau Physiographic Province (McElroy, 2000). The basin is primarily within Somerset County, but small sections of the basin on the western periphery along Laurel Hill are in Fayette and Westmoreland Counties (fig. 1). There is relatively large relief in the basin compared with the rest of the State, with elevations ranging from 1,300 feet (ft) (above North American Vertical Datum of 1988 (NAVD 88) at the outlet of the basin at Confluence, Pa., to approximately 2,990 ft on Laurel Hill (fig. 2). The western boundary of the basin is Laurel Hill, and elevations decrease from west to east. The eastern boundary of the basin is a low drainage divide with the Casselman River.

The Laurel Hill Creek Basin is 79 percent forested and 20 percent agricultural land, with only 1 percent of land developed as high/low density residential and quarries (U.S. Geological Survey, 2004; Mackin Engineering Company, 2010) (fig. 3). According to the 2000 Census (U.S. Census Bureau, 2000), approximately 2,700 people reside in the basin. The most highly concentrated population densities occur in the southern tip of the basin in the towns of Ursina and Confluence (fig. 1). Smaller densities occur in the upper and middle sections of the basin. Future population increases are likely to occur in the middle to upper sections of the basin along the Route 31 corridor near and to the east of Bakersville, Pa. Also, there is the potential for the two resorts in the basin, Seven Springs Mountain Resort and Hidden Valley Resort, to increase the number of housing units over the next 15 years (Mackin Engineering Company, 2010).

Twenty-nine percent of the basin is state-owned land (Crouse & Company of Somerset and Kleinschmidt Group, 2005), which includes three State parks, State forest, and State game lands. These State lands are relatively pristine and are used primarily for recreational activities.

Climate

Annual precipitation in the basin varies spatially due to the mountainous terrain, which causes substantial orographic influences on precipitation patterns (fig. 4). For the Laurel Hill Creek Basin, the overall average precipitation for 1971–2000 was 48 inches per year (in/yr) with the variation in grid cells ranging from 44 to 58 in/yr. (PRISM Climate Group, Oregon State University, 2011). The PRISM Climate Group populated the basin with average climatic data using cell sizes of 800 meter (m) by 800 m (514 cells for the entire basin). The highest values for average precipitation occurred in the northwestern corner of the basin. The only continuous climate station in the basin is in Confluence, Pa., at the southern tip of the basin (fig. 1). The average precipitation for this station during 1971–2000 was 45.5 in/yr (National Climate Data Center, 2004).

Snowfall varies greatly across the basin, both spatially and seasonally. Snowfall totals recorded at Seven Springs Mountain Resort (fig. 1) from fall 2005 through spring 2010 indicate an annual average snowfall for the period of 135 inches (in.), with the minimum occurring during the 2008–09 season (98 in.) and the maximum occurring during 2009–10 (223 in.) (Jeffrey Alcorn, written commun., 2011). The average annual snowfall was 54.9 in. at Confluence for 1971–2000 (National Climate Data Center, 2004). The snow totals for Seven Springs and Confluence probably provide a reasonable estimate of the snow fall range within the basin.

Air temperatures vary across the basin owing to orographic influences. The annual average of daily maximum air temperatures range from 53.5 to 61.5 degrees Fahrenheit (^{o}F) (fig. 5) and average of daily minimums range from 35.6 to 39.3 ^{o}F (fig. 6) (PRISM Climate Group, Oregon State University, 2011). On the basis of temperature data from continuous recording stations in and around the basin, the highest daily maximums and minimums occur in July, and the lowest

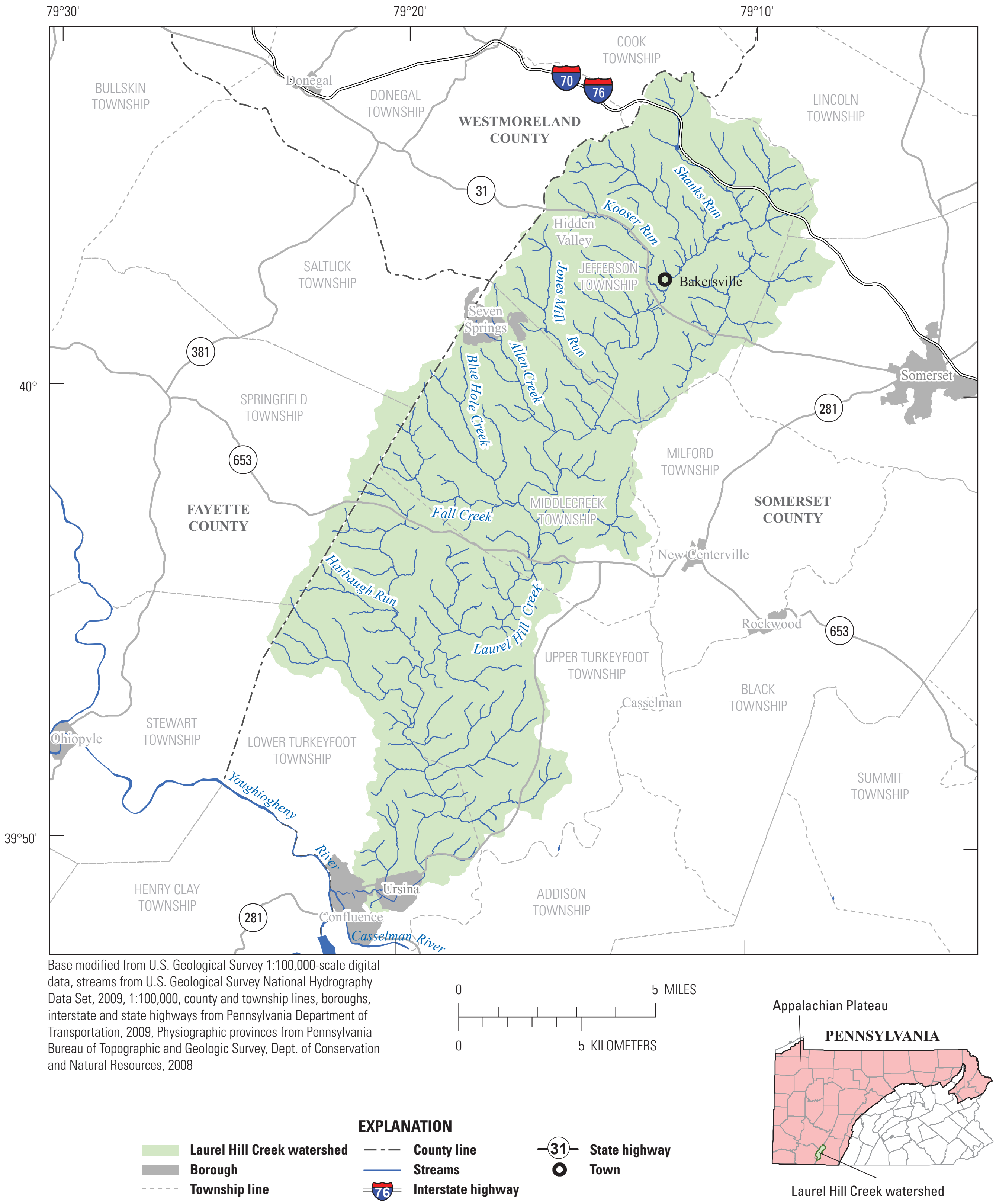


Figure 1. Laurel Hill Creek Basin, southwestern, Pennsylvania.

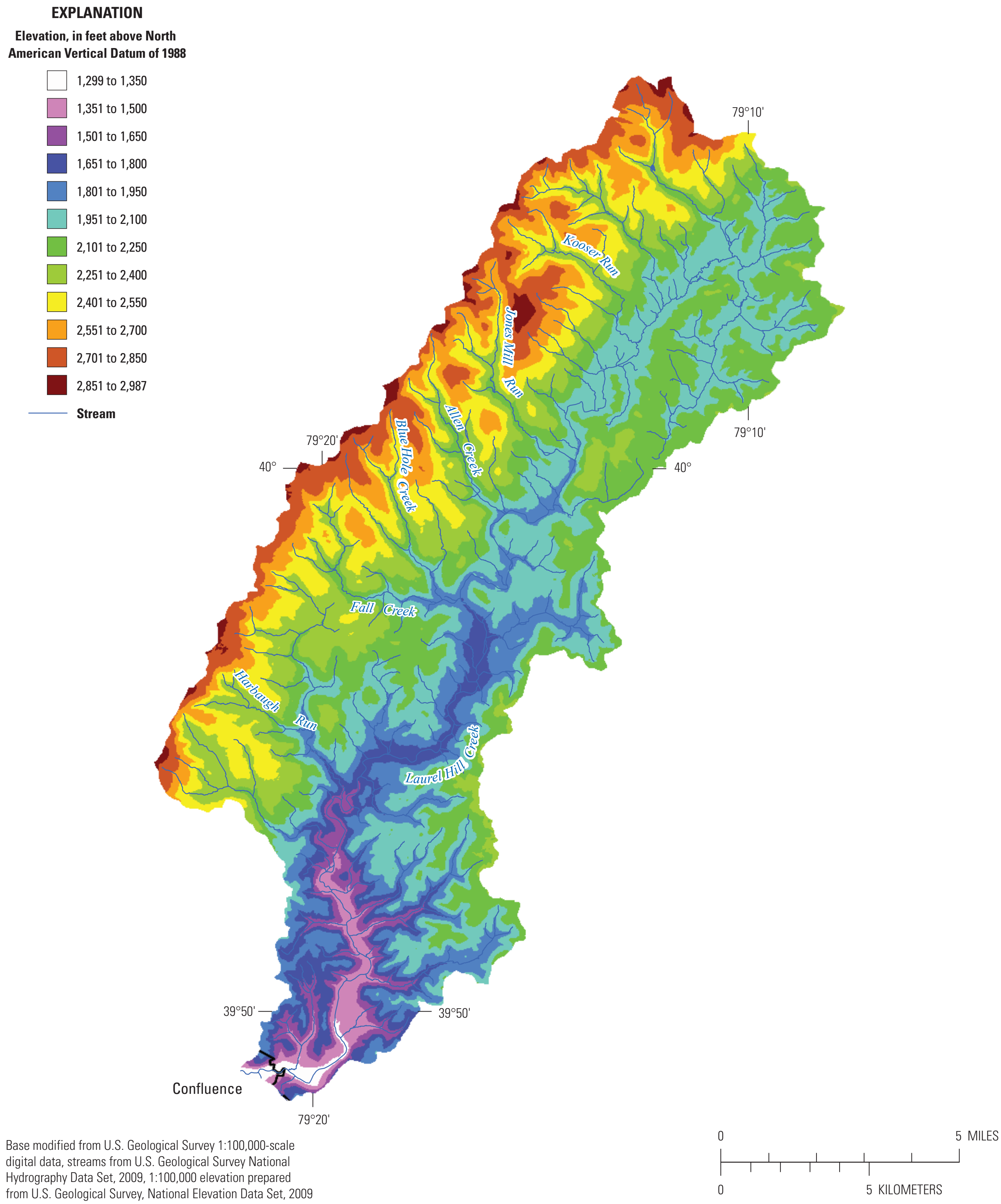


Figure 2. Topographic elevations in Laurel Hill Creek Basin, southwestern, Pennsylvania.

Base modified from U.S. Geological Survey 1:100,000-scale digital data, streams from U.S. Geological Survey National Hydrography Data Set, 2009, 1:100,000, interstate and state highways from Pennsylvania Department of Transportation, 2009

Land use and land cover from U.S. Geological Survey, 2004

Figure 3. Land use and land cover in Laurel Hill Creek Basin, southwestern, Pennsylvania, 2001.

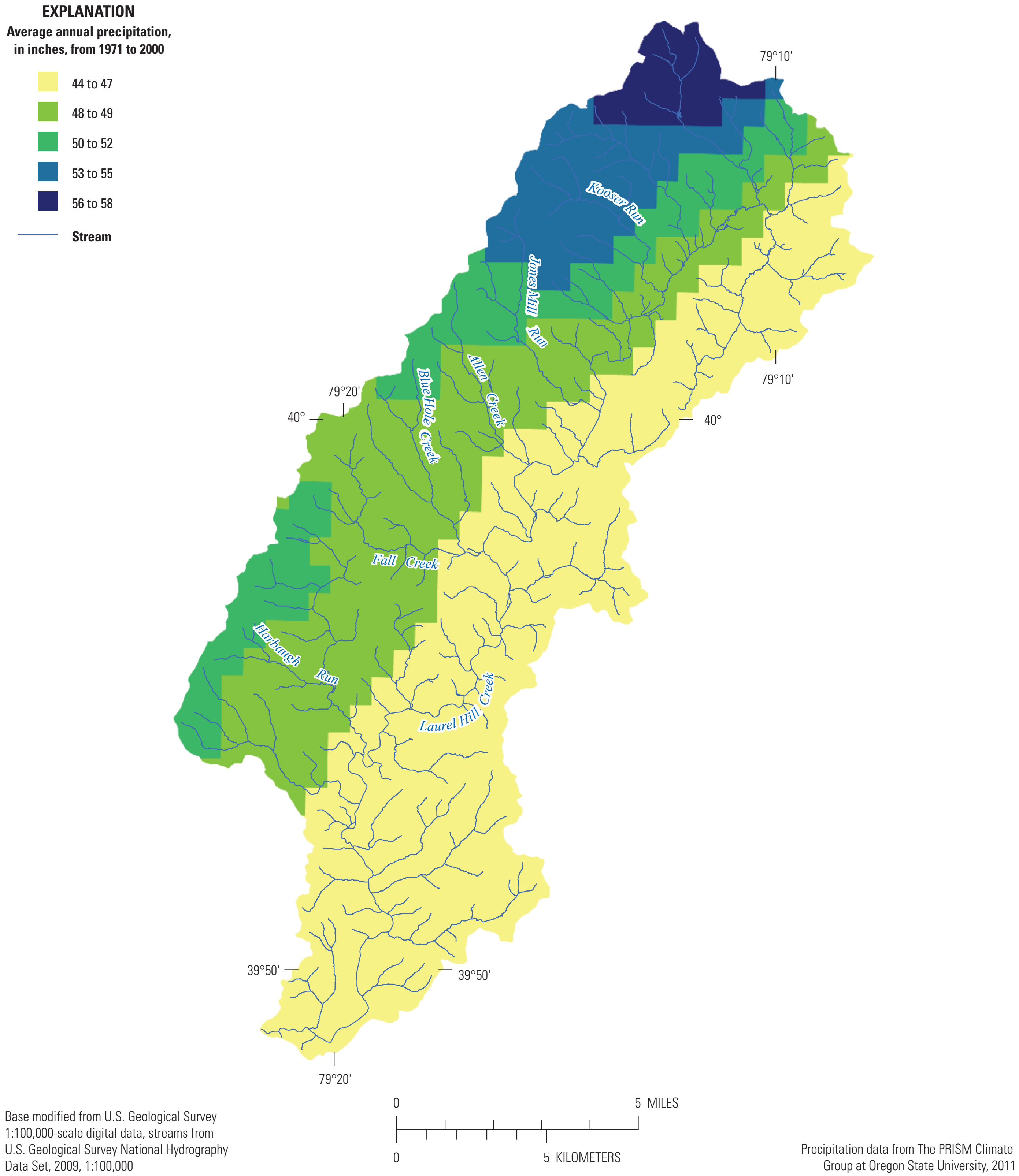


Figure 4. Average annual precipitation in the Laurel Hill Creek Basin, southwestern, Pennsylvania, from 1971–2000.

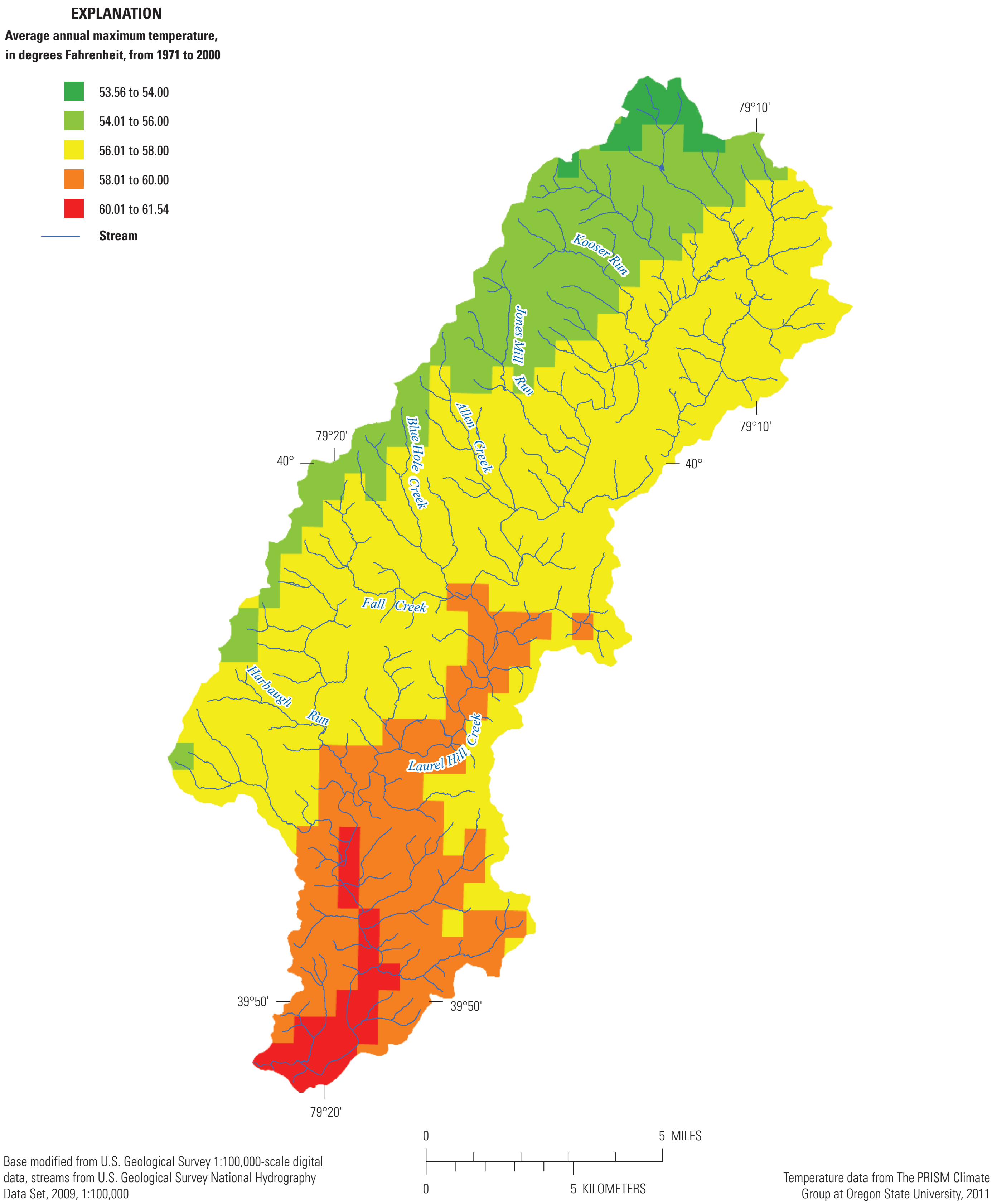


Figure 5. Average annual daily maximum air temperatures in the Laurel Hill Creek Basin, southwestern, Pennsylvania, 1971–2000.

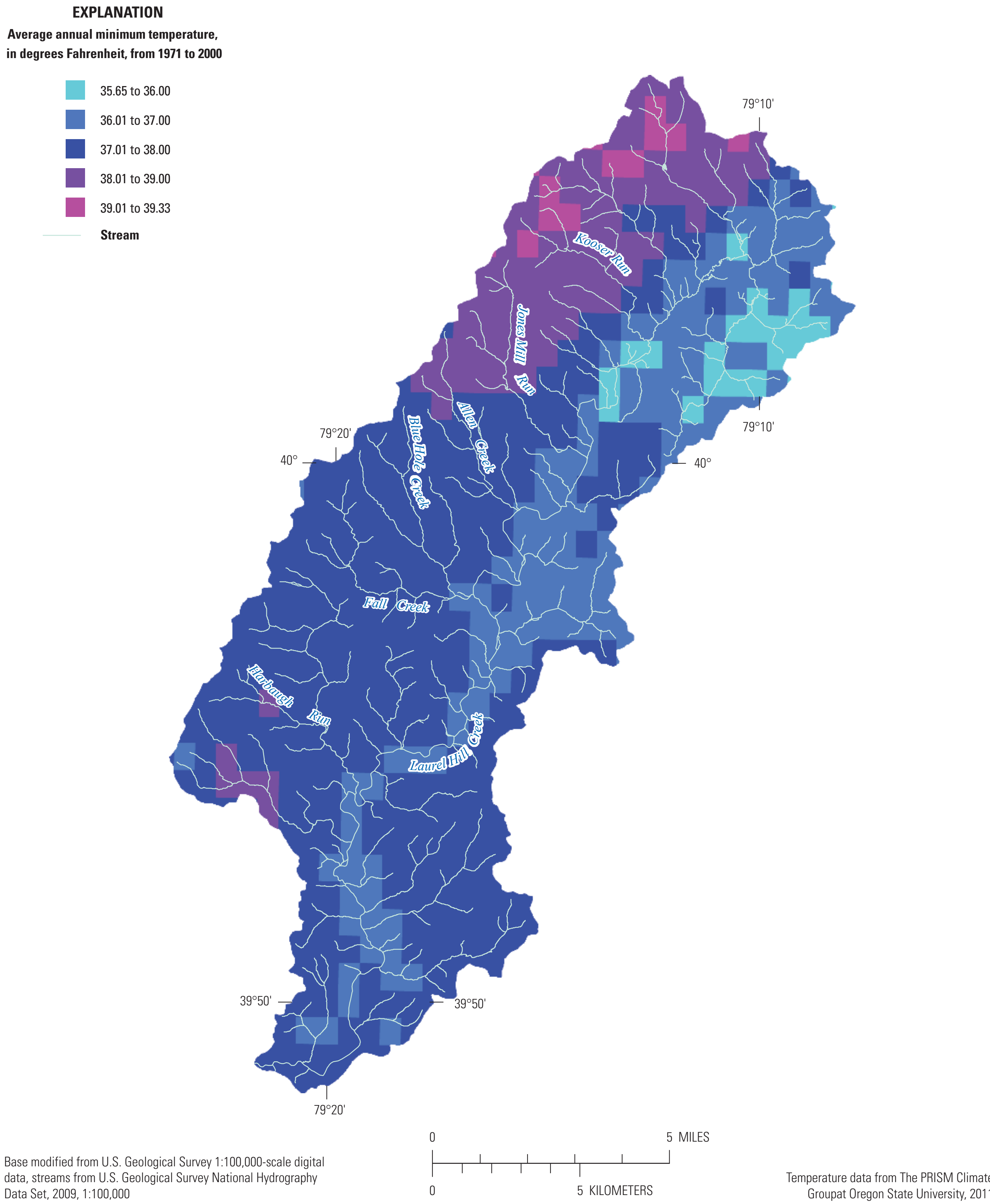


Figure 6. Average annual daily minimum air temperatures in the Laurel Hill Creek Basin, southwestern, Pennsylvania, 1971–2000.

daily maximums and minimums occur in January. The daily maximums range from about 75 to 85 °F in July, and the daily minimums range from about 15 to 16 °F in January (National Climate Data Center, 2004).

Geologic Setting

The Laurel Hill Creek Basin is underlain by sedimentary rock of the Mississippian to Pennsylvanian period, which occurred from 300 to 360 million years ago. The oldest rock exposed in the basin is that of the Mississippian-aged Burgoon Sandstone, which is overlain by the Loyalhanna Formation (limestone), then by the Mauch Chunk Formation. The Mauch Chunk Formation consists of interbedded shale/sandstones with a few beds of siltstone/limestone (Geyer and Wilshusen, 1982). The oldest Pennsylvanian-aged rocks in the basin are of the Pottsville Group, followed by the Allegheny Group, and the Conemaugh Group (composed of the Glenshaw and Casselman Formations) (McElroy, 2000). The Pottsville Group consists primarily of sandstone with interbedded shale and minor amounts of coal, claystone, siltstone, and limestone. The Allegheny group consists of alternating layers of shale, claystone, siltstone, sandstone, and coal (Geyer and Wilshusen, 1982; Crouse & Company of Somerset and others, 2005). The Glenshaw and Casselman Formations in the Conemaugh Group are heterogeneous formations. The Glenshaw Formation consists of repeated sequences of sandstone, siltstone, claystone, limestone, and coal, whereas the Casselman Formation is composed of alternating layers of shale, siltstone, sandstone, and some thin limestone layers (Crouse & Company of Somerset and Kleinschmidt Group, 2005). The Mississippian-age rocks predominate in the west to northwestern section of the basin, whereas the Pennsylvanian-age rocks dominate in the remaining sections of the basin. The most common rock underlying the surface is the Allegheny Formation, followed by the Casselman and Pottsville Formations (fig. 7).

All of the rock formations in the Laurel Hill Creek Basin potentially can yield large quantities of groundwater. The public-supply wells in the basin are completed in the Mauch Chunk Formation. The Loyalhanna Formation is the source of at least two public-supply wells in other parts of Somerset County, and the Burgoon Sandstone also can be an excellent water source (McElroy, 2000). Iron and manganese concentrations greater than the U.S. Environmental Protection Agency (EPA) secondary maximum contaminant levels (SMCLs) do occur on a regular basis in each formation (McElroy, 2000). SMCLs are non-enforceable Federal guidelines regarding cosmetic or aesthetic effects. The SMCL for iron is 300 micrograms per liter (µg/L) and the SMCL for manganese is 50 µg/L (U.S. Environmental Protection Agency, 2012). The Allegheny and Pottsville Formations can also yield acidic groundwater, which can corrode plumbing.

Soil genesis in the basin was greatly affected by slope. Most soils in the basin are deep. Soils along the ridges and hill sides generally are well drained, whereas low land soils in the flood plain generally are poorly drained. The most common soils in the basin are the Rayne-Gilpin loams (U.S. Department of Agriculture, Natural Resource Conservation Service, 2004a, 2004b, 2006) that occur throughout the basin, except along the narrow ridge tops. Rayne-Gilpin loams formed in materials weathered from shale and siltstone and are moderately permeable and moderately erodible. They can be used for cropland and pasture but generally are limited to non-agricultural uses due to a typically shallow bedrock layer of 2–6 feet (Yaworski, 1983). The second most common soil series in the basin is the Wharton series, which is derived from acidic shales. In the basin, the Wharton series generally has a silt loam texture, is moderately deep and well drained, is only slightly erodible, and is found on broad ridges and hill tops (Yaworski, 1983). These soils also can be used for cultivated crops and pasture. The third most common soil series is the Ernest soils, which are derived in colluvium from weathered shale and siltstones. The Ernest series in the basin has a silt loam to very stony silt loam texture, and these soils are deep, moderately well drained, and moderately erodible. They are found on the side slopes of hills and ridges. The phases of Ernest soil that are silt loam in texture can be used for crops and pasture, but the very stony loam texture soils of the Ernest series can be used only for trees (Yaworski, 1983).

Hydrography

Laurel Hill Creek enters the Casselman River approximately 400 ft before the Youghiogheny River in the Borough of Confluence (fig. 1). The stream network in the Laurel Hill Creek Basin is extensive. The main stem of Laurel Hill Creek flows for approximately 38 miles with the head waters of the creek originating just south of Route 31 (southeast of Bakersville) about 5 miles west of the town of Somerset. The creek flows north towards the Pennsylvania Turnpike (Interstate 76) but makes a bend just south of the turnpike and eventually flows in a generally southerly direction until it discharges into the Casselman River. Thirty-two named tributaries and many unnamed tributaries flow into Laurel Hill Creek. The named tributaries consist of 145 miles of stream (Crouse & Company of Somerset and Kleinschmidt Group, 2005). The main stem of Laurel Hill Creek could be considered a low-gradient stream because the slope is much flatter than that of the tributary subbasins. The tributaries, especially those on the western half of the basin that originate along the ridges, are more indicative of high-gradient streams due to the steep slopes. The tributaries in the eastern half of the basin have stream gradients that are similar to the main stem. The high gradient tributaries transport sediment rapidly to the main stem, whereas the tributaries to the east may tend to accumulate some sediment in their channels, and the transport to the main stem is more episodic. The drainage network in the basin is an integration of dendritic and parallel drainage patterns. A dendritic pattern (similar to a tree root pattern) occurs in areas where the underlying material is homogeneous, indicating that the subsurface geology has a similar resistance to weathering. A parallel drainage pattern occurs if slope controls flow patterns (Ritter, 2010).

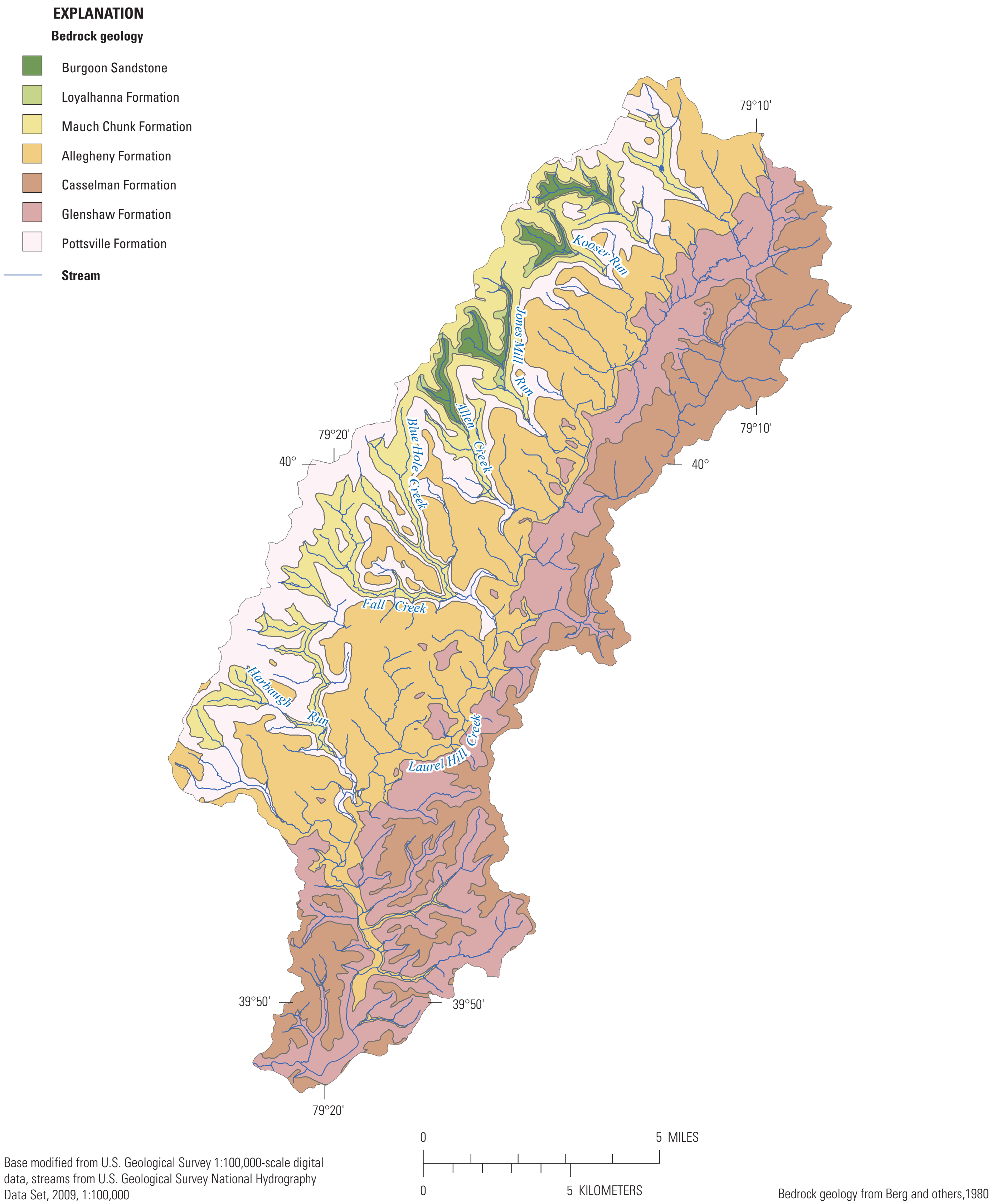


Figure 7. The bedrock geology in Laurel Hill Creek Basin, southwestern, Pennsylvania.

Historically, water quality in the basin has been relatively good, especially considering that some of the surrounding basins are affected by mine drainage. A snapshot of water quality in the Laurel Hill Creek Basin was conducted during 2002–03 as part of the Rivers Conservation Plan. The primary water-quality concern identified in the Rivers Conservation Plan was low pH values for various tributaries resulting from acidic precipitation and (or) weathering of pyritic bedrock (Crouse & Company of Somerset and Kleinschmidt Group, 2005).

Part of the drainage network in the Laurel Hill Creek basin also has been identified as impaired by PaDEP (2011, 2014). In the upper part of the basin, 5.5 miles of a tributary and 35.5 miles of the main stem of Laurel Hill Creek are on the 2014 impaired stream list [303(d) list of PaDEP (2014)]. The tributary is impaired by nutrients (grazing related agriculture) and the main stem by organic enrichment, low dissolved oxygen, and siltation.

Methods

Water-quality and -quantity data were collected in the Laurel Hill Creek Basin during summer and fall 2007 to characterize the base-flow hydrology of the Laurel Hill Creek and the various groundwater aquifers in the basin. The amount of water used for human activities was documented using WAST on the basis of water-use data compiled for 2003 and 2009. The GSFLOW model was applied to integrate groundwater and surface-water components of the hydrologic system and to allow for water budget estimation for any location within the stream drainage network.

Water Quality

As described in more detail below, water-quality samples were collected twice in the summer-fall of 2007 during base-flow or non-recharge conditions. Stream temperature probes were installed along the main stem of Laurel Hill Creek in 2007 and operated to 2010 to characterize the spatial and temporal variations in water temperature and determine whether the thermal conditions of the stream were consistent with a system defined as a HQ-CWF.

Surface Water

Two surface-water synoptic surveys were conducted in the Laurel Hill Creek Basin on June 25–27 and September 17–19, 2007, during periods of static base flow. No significant precipitation occurred within the basin during and immediately before (4 days or less) either of the synoptic sampling periods. Thirty-seven sites were sampled during both of the synoptic studies; 31 of the sites were sampled during both synoptic studies (fig. 8). Twelve sites along the main stem of Laurel Hill Creek and 25 sites on tributaries to the main stem were sampled. Many of the surface-water sites selected for sampling were previously sampled as part of the work conducted for the Rivers Conservation Plan (Crouse & Company of Somerset and Kleinschmidt Group, 2005).

Grab samples were collected using depth and width-integrated measuring techniques. Field measurements included specific conductance (SC), pH, DO, and water temperature. Streamflow was measured concurrent with sampling. Alkalinities and acidities were determined in the field or at the USGS water laboratory in New Cumberland, Pa. Alkalinities were determined using the fixed endpoint (pH = 4.5) method, and acidities were determined using the hot-peroxide acidity method (American Public Health Association and others, 1992). Samples were filtered in the field through a 0.45-micron filter and chilled prior to shipment to the USGS National Water Quality Laboratory (NWQL) in Denver, Colorado, for chemical analyses in accordance with methods of Fishman (1993). Water samples were analyzed for dissolved concentrations of calcium (Ca), magnesium (Mg), sodium (Na), iron (Fe), manganese (Mn), aluminum (Al), chloride (Cl), sulfate (SO_4), nitrate plus nitrite ($NO_3 + NO_2$), nitrite (NO_2), ammonia (NH_3), and phosphate (PO_4). Total concentrations of nitrogen (N) and phosphorus (P) also were analyzed.

Water-temperature probes were deployed at five locations along the main stem of Laurel Hill Creek stream network (fig. 9). The length of the main stem of Laurel Hill Creek from the head waters to where it drains into the Casselman River at Confluence, Pa., is about 38 stream miles. The temperature probe farthest upstream was approximately 7 miles from the start of Laurel Hill Creek identified as perennial on the USGS topographical map (1:24,000) for Bakersville, Pa. The farthest downstream temperature probe was located at Ursina, Pa., about 2 miles from the confluence of Laurel Hill Creek with the Casselman River. The temperature loggers were programmed to record temperature every 30 minutes from July 2007 until time of removal or the loggers were damaged. Data were recorded at two sites until November 2009, one site until April 2010, and two sites until July 2010. Site selection was based on critical areas identified by stakeholders. In addition, some type of structure such as a bridge abutment, was necessary to secure the loggers and avoid sensor movement. Temperature probes were attached to bridge abutments using cable wire and lag bolts. The probes did not move more than 2–3 ft after installation; therefore, the amount of sunlight that each probe was subjected to was dependent on changes in the angle of the sun caused by season.

Groundwater

Two groundwater synoptic surveys were conducted in the Laurel Hill Creek Basin in 2007. The first synoptic was conducted July 23–25 and August 1, 2007, and the second synoptic was conducted October 1–3, 2007. During and immediately before (four days or less) each synoptic study, recharge to the groundwater table was negligible. No recharge events occurred prior to, or during, sampling of the groundwater. To

Figure 8. Surface-water sites sampled for water quality and streamflow in Laurel Hill Creek Basin, southwestern Pennsylvania, June and September 2007.

Figure 9. Locations of stream-temperature probes in Laurel Hill Creek, southwestern, Pennsylvania.

select sampling sites, a grid with cell sizes of approximately 5–6 mi^2, was placed over the basin map. A well or spring within each grid cell was selected and sampled. A total of 19 groundwater wells and 7 springs were sampled during the two synoptic studies; water from 14 of the wells and 4 of the springs was sampled for both synoptic studies (fig. 10). Three of the sampled wells are public-supply wells, the remaining sites are domestic wells or springs. Groundwater samples were collected before water passed through any water-purification device. Field measurements included SC, pH, DO, oxidation-reduction potential (REDOX), water temperature, and depth of water in the well below land surface. The water level in the well was recorded prior to any pumping necessary to collect the water-quality sample. Alkalinities and acidities were determined in the field or at the USGS water laboratory in New Cumberland, Pa. Alkalinities were determined using the fixed endpoint (pH = 4.5) method, and acidities were determined using the hot-peroxide acidity method (American Public Health Association and others, 1992). Water samples from wells were collected after the SC and water temperature remained stable for 3–5 minutes. Samples were filtered in the field through a 0.45 micron filter and chilled prior to sample shipment to the USGS NWQL for chemical analyses of Ca, Mg, Na, Fe, Mn, arsenic (As), Cl, SO_4, silica (SiO_2), NO_3 + NO_2, NO_2, and NH_3 in accordance with methods of Fishman (1993). For springs, analysis also included Al and the discharge for each spring was measured if possible.

Water Quantity

The volume of water discharging from the various subbasins and at numerous locations along the main stem of Laurel Hill Creek was quantified twice during low-flow periods in the summer and fall 2007, as described below. These data were used to show the percent contribution of subbasin streamflow of the total flow in the main stem. The WAST was implemented to determine the status of water use in the basin and the manner in which water use is potentially affecting the streamflow in the main stem.

Streamflow Characterization

Streamflow measurements at multiple cross sections along the length of the main stem of the Laurel Hill Creek and tributaries were conducted during low-flow periods with stable flow conditions. The streamflow measurements were conducted at the same time as the surface-water synoptics, so the measurements were conducted June 25–27, 2007, and Sept. 17–19, 2007. Streamflow was measured twice at 31 stream cross sections and once at 6 other locations. Streamflow measurements were conducted at 25 tributary sites and 12 main-stem sites on Laurel Hill Creek (fig. 8). The USGS streamflow-gaging station on Laurel Hill Creek at Ursina, Pa. (station 03080000), was used to determine whether stable conditions existed. No precipitation occurred prior to or during sampling; therefore, streamflow conditions were virtually static. Streamflow was measured by wading in the stream, establishing a cross section, and using an acoustic Doppler velocimeter (ADV) to measure velocity. This type of current meter uses an adaptation of the Doppler principle to measure water velocity by processing sonar reflected from suspended particulates (SonTek, 2003). Velocity and water depth were measured at 10–28 locations along each cross section. Smaller tributaries required fewer measurement locations along a cross section. The streamflow data were used to quantity the amount of water from the tributaries that contributes to the flow of the main stem of Laurel Hill Creek, and to determine where the main stem of Laurel Hill Creek was gaining or losing water to or from the shallow groundwater system. Water-withdrawal locations along the main stem were mapped to better understand results from the streamflow measurements. Drainage areas for each site were determined so that a flow per unit area could be determined.

Water Use

Water-use data for the Laurel Hill Creek Basin were compiled by PaDEP and USGS for 2003 and by the USGS for 2009. Water use was determined for both groundwater and surface-water withdrawals, and these were summed to determine a total amount of water use for the entire basin. The water-use data were verified by communicating with significant water users [a significant water user is defined as any entity withdrawing 10,000 gallons per day (gal/d) or more]. All water users withdrawing or using more than 10,000 gal/d averaged over a 30-day period and all public water agencies are required to register their water use with PaDEP (Stuckey, 2008). Registered users include water suppliers, some commercial entities, and some mineral resource companies; however, only public water suppliers need to report actual monthly water use to PaDEP. Therefore, withdrawals were estimated for some registered and all unregistered users. Unregistered users include four groups: self-supplied residential, industrial companies, any remaining commercial entities, and agricultural users. The derivation of water-use estimates for non-registered users is discussed by Stuckey (2008). For residential users (private well or spring) with septic systems, it was assumed that households used 80 gal/d with 90 percent of the water going back to the system (only 10 percent consumptive use) (Stuckey, 2008). For the Laurel Hill Creek Basin, all residential water users were assumed to use septic systems.

The Laurel Hill Creek Basin supplies public water within and outside the basin boundaries; in addition, many homeowners, businesses, and farms in the basin have private systems that tap either groundwater wells or springs for water supply. The local water authorities and municipalities withdraw groundwater and surface water within the basin (fig. 11). According to 2003 water-use data compiled by PaDEP and verified by the USGS, the total withdrawals in the basin averaged 2.27 million gallons per day (Mgal/d) with 0.26 Mgal/d discharged back into the system for a net withdrawal rate

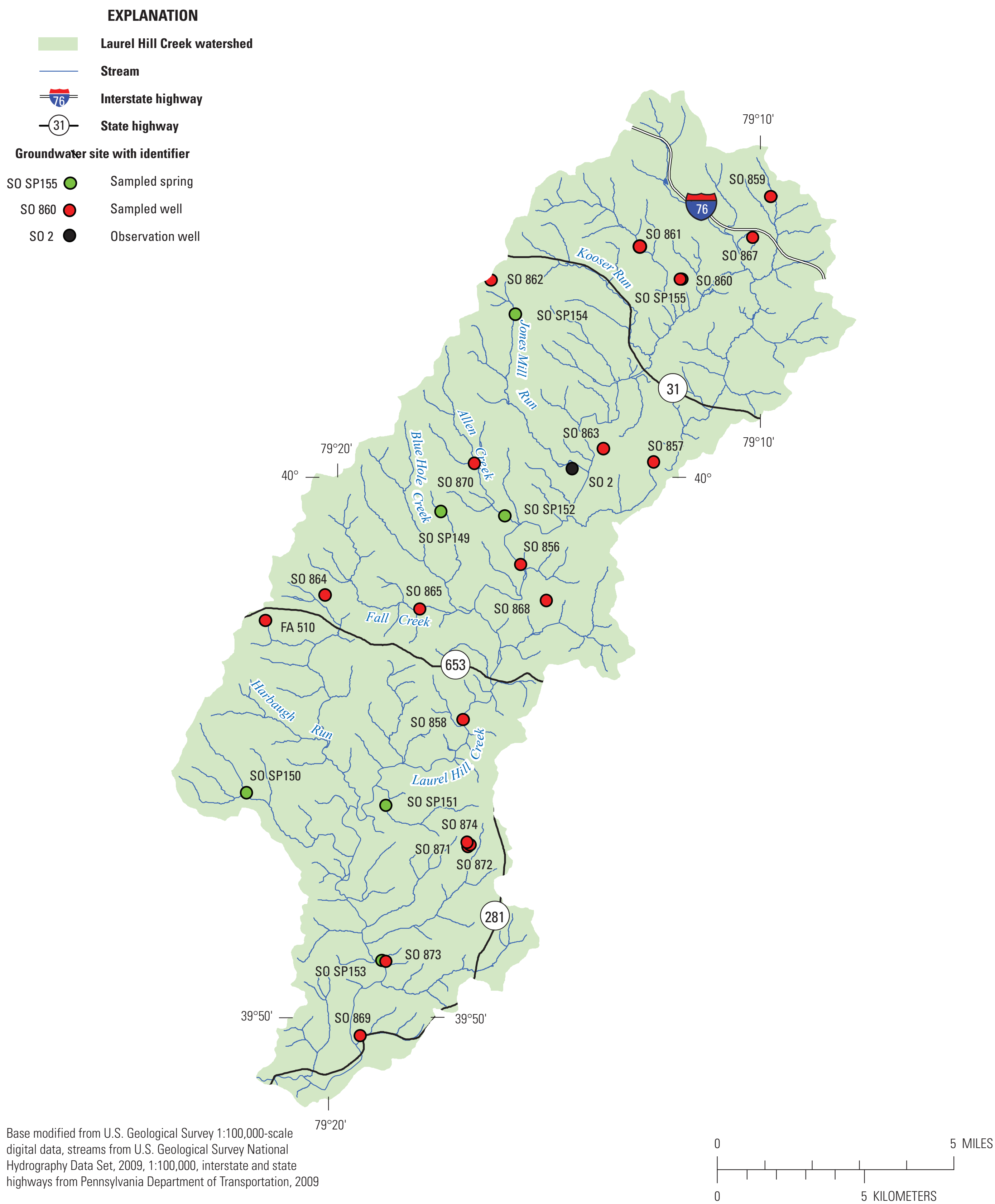
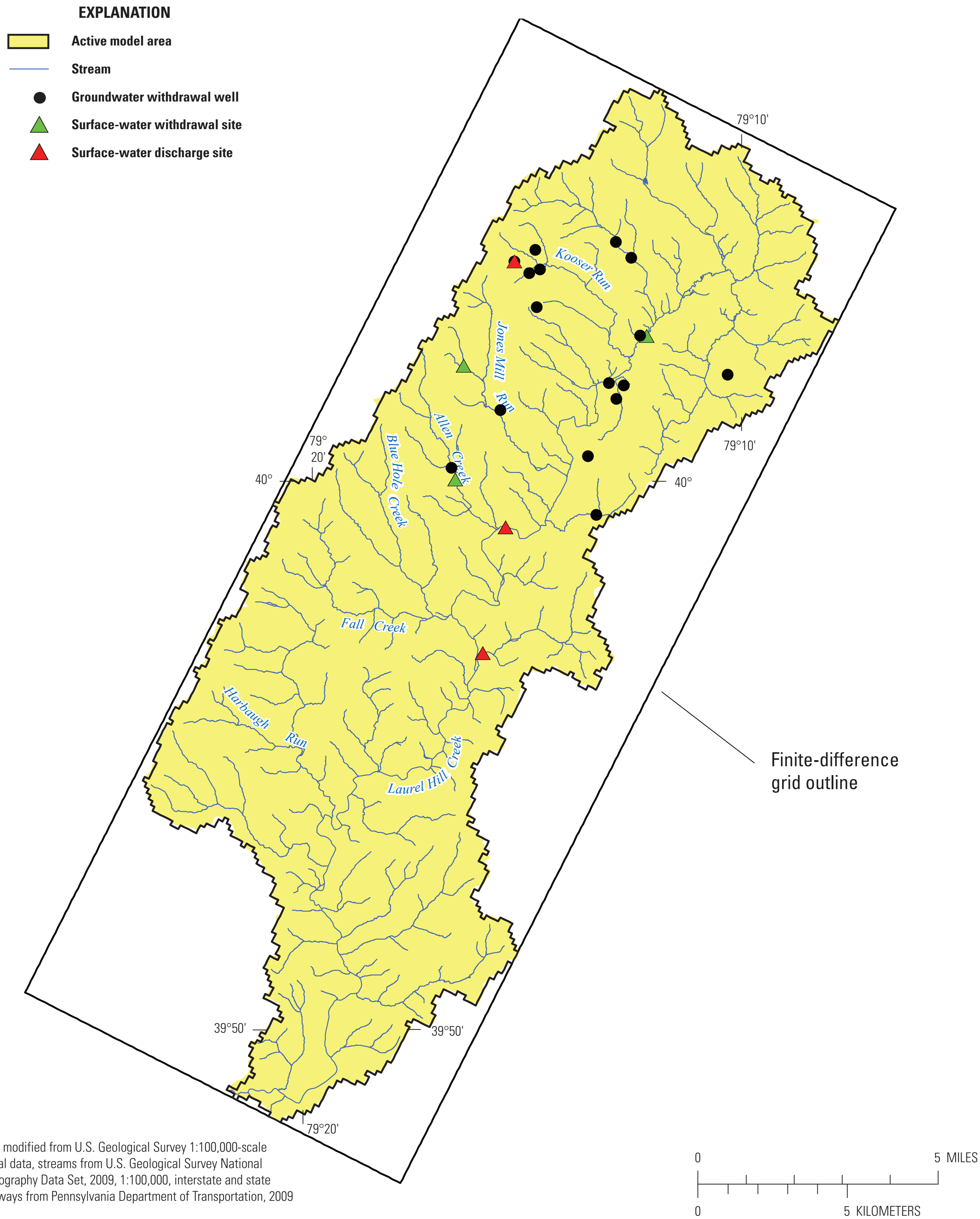


Figure 10. Locations of groundwater sites sampled for water quality and the U.S. Geological Survey observation well for Somerset County in Laurel Hill Creek Basin, southwestern, Pennsylvania, July–August and October 2007.



Base modified from U.S. Geological Survey 1:100,000-scale digital data, streams from U.S. Geological Survey National Hydrography Data Set, 2009, 1:100,000, interstate and state highways from Pennsylvania Department of Transportation, 2009

Figure 11. Locations of registered groundwater-withdrawal well sites and sites of permitted discharges to, and registered withdrawals from, surface water in Laurel Hill Creek Basin, southwestern, Pennsylvania.

of 2.01 Mgal/d. Surface-water withdrawals accounted for 1.18 Mgal/d, and groundwater withdrawals accounted for the remainder. Most of the withdrawals within the basin were made by public water suppliers, who account for 68 percent of the net withdrawals (Marla Stuckey, U.S. Geological Survey, written commun., 2008) (fig. 12).

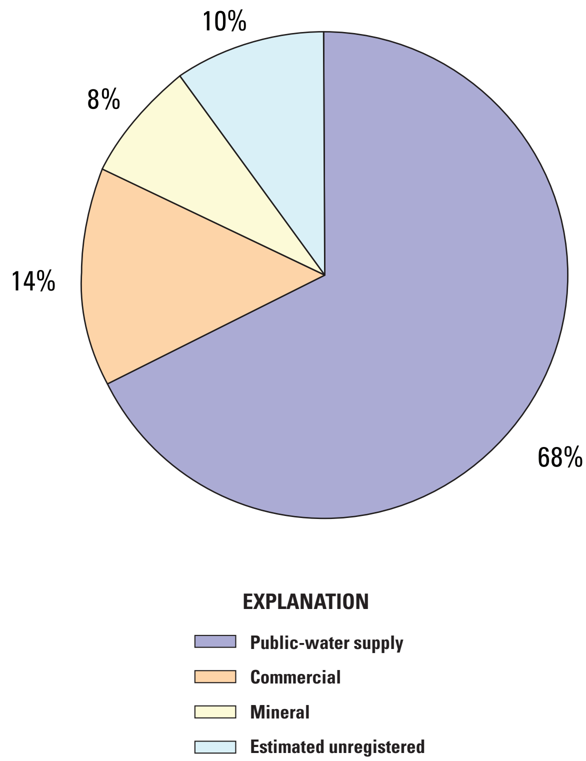


Figure 12. Percentage of water withdrawn, by selected categories, within Laurel Hill Creek Basin, southwestern, Pennsylvania, using 2003 water-use data.

The remaining withdrawals were made for commercial, unregistered (self-supplied for domestic or agricultural use), and mineral extraction uses. According to criteria established by the Commonwealth of Pennsylvania for Act 220, the net withdrawal of 2.01 Mgal/d exceeds the safe yield estimate of 1.43 Mgal/d for the basin. Safe yield is defined by PaDEP (2006b) as follows:

"For purposes of the State Water Plan, the amount of water that can be withdrawn from a water resource over a period of time without impairing the long-term utility of a water resource such as dewatering of an aquifer, impairing the long-term water quality of a water resource, inducing a health threat, or causing irreparable or unmitigated impact upon reasonable and beneficial uses of the water resource. Safe yield of a particular water source is primarily to be determined based upon the predictable rate of natural and artificial replenishment of the water source over a reasonable period of time."

Water-Analysis Screening Tool (WAST)

The WAST was run for the Laurel Hill Creek Basin using 2003 and 2009 water-use data. The WAST compares water-use information to an initial screening criteria (ISC) that is a percentage of the 7-day, 10-year low-flow statistic (7Q10). The 7Q10 is defined as the lowest consecutive 7-day mean flow expected on average every 10 years. For areas not underlain by carbonate rock, the ISC is equal to one-half the value of the 7Q10. The net withdrawals in the basin are subtracted from the ISC value, with the result equal to the screening indicator (SI) expressed in Mgal/d. The SI is negative if net withdrawals exceed the ISC value. The SI value is divided by the ISC in order to generate a dimensionless screening indicator. This dimensionless screening indicator is multiplied by 100 to generate a screening indicator as a percentage (SIP). The SIP values are generated for different points (pour points) along the stream network to determine the potential for conflicts between water use and aquatic resources. Negative SIP values indicate the potential for conflicts between water use and aquatic life (Stuckey, 2008). At each pour point, the drainage area is determined, the water use (from groundwater and surface-water sources) in the drainage basin is estimated by the WAST, and the WAST accesses the 7Q10 estimated using statewide regression equations (Stuckey, 2006). The statewide regression equations were developed using data from 293 streamflow-gaging stations that were not affected by regulation, diversion, or mining. These equations are based on the physical characteristics of the gaged watersheds; some significant explanatory variables are drainage area, basin slope, soil thickness, stream density, precipitation, elevation, bedrock geology, and land use (Stuckey, 2006). With this information, SI and SIP values are generated, and this process can be conducted for numerous points within the stream network.

The 7Q10 used by the WAST was computed using regional regression equations developed by the USGS. Although there is a USGS streamflow-gaging station on Laurel Hill Creek at Ursina, Pa. (established in 1918), the 7Q10 for this station was not used to determine the theoretical 7Q10 because there are substantial daily water withdrawals from the system. Data from 293 streamflow-gaging stations were used in the regression equations developed to define statewide 7Q10 values (Stuckey, 2006).

For the State Water Plan, standard procedure was to use the WAST primarily for the main stem or the primary water body that drains the basin. For this study in the Laurel Hill Creek Basin, the WAST was used for both the main stem and selected tributary basins. Water in the Laurel Hill Creek Basin is withdrawn for water supply from both groundwater and surface-water sources. Most of the groundwater withdrawals for water supply occur in subbasins along the western periphery of the basin in upland areas. These upland areas are underlain by the Mauch Chunk Formation, which is known to yield large quantities of potable groundwater (McElroy, 2000). Although the WAST was developed for basins that are primarily greater than or equal to 15 mi^2 (Stuckey, 2008), in this study, WAST results were generated for some subbasins less than 15 mi^2 in areas underlain by the Mauch Chunk Formation where groundwater withdrawals were substantial.

Water-use data for the Laurel Hill Creek Basin also were compiled for 2009. The 2009 water-use data were obtained by direct communication with water users. Once the data were final, the WAST was rerun. Also, water use is most critical during drought conditions. For the Laurel Hill Creek Basin, the WAST was run for drought conditions and more typical or "normal" streamflow conditions. During drought conditions, one of the major water suppliers in the Laurel Hill Creek Basin has to meet a pass-by requirement before surface water can be withdrawn; therefore, when flows are low, the withdrawal from surface water is reduced (and SI values increase).

GSFLOW Model

GSFLOW (a groundwater and surface-water flow model developed by the USGS) is an interactive model that ties together different hydrological modeling programs. The two major components of GSFLOW are PRMS (a precipitation–runoff modeling system) and MODFLOW (the groundwater component). GSFLOW is a physically based, distributed model developed to simulate coupled groundwater/surface-water flow in one or more basins by simultaneously simulating flow across the land surface and within subsurface saturated and unsaturated materials (Markstrom and others, 2008). The GSFLOW model is a tool that, when used in coordination with the WAST, can help to identify whether areas under water stress are primarily groundwater or surface-water related. GSFLOW can be used to evaluate the effects of land-use change, different precipitation patterns, and groundwater and (or) surface-water withdrawals on subsurface and surface flow (Markstrom and others, 2008).

GSFLOW simulates flow in three distinct regions, one of which is governed by processes and variables defined in PRMS, and the other two are governed by processes and variables defined in MODFLOW (Markstrom and others, 2008). The uppermost region extends from the top of the plant canopy to the bottom of the soil zone (or rooting depth) and is the region defined by PRMS. The second and third regions are defined by MODFLOW. The second region includes water flowing across the land surface and in streams and lakes; the third region includes subsurface water. Prior to the coupling of PRMS and MODFLOW in GSFLOW, both PRMS and MODFLOW were calibrated to observed conditions. For the GSFLOW model developed for the Laurel Hill Creek Basin, the PRMS and MODFLOW models were calibrated to streamflow data available for the USGS streamflow-gaging station in Ursina, Pa., which has been active since 1918. MODLFOW also was calibrated to water-level elevations for a network of wells that were sampled in 2007 during the groundwater synoptic sampling (see fig. 11). The entire Laurel Hill Creek Basin encompasses 125 mi^2 that drain into the Casselman River. At the gage at Ursina, Pa., the drainage area is 121 mi^2. The streamflow data computed for the Ursina, Pa., streamflow-gaging station from Jan. 1, 1991, through September 30, 2007, were used to calibrate the GSFLOW model. Daily values from the Ursina streamflow record were retrieved and used as the observed values for the model. The GSFLOW model was run on a daily time step. Stormflow simulation was not necessary for this model because daily values of streamflow were adequate for the model calibration process.

MODFLOW Overview

The finite-difference computer code MODFLOW-NWT (Niswonger and others, 2011) was used to simulate steady-state groundwater flow in the Laurel Hill Creek Basin. MODFLOW-NWT is a code based on MODFLOW-2005 (Harbaugh, 2005), but it has better capabilities for solving the groundwater-flow equation for highly nonlinear problems. A graphical user interface linked to Argus Numerical Environments was used for pre- and post-processing of data (Winston, 2000). Input datasets to MODFLOW–NWT describe the hydrogeologic units of the basin, unsaturated zone, boundary conditions, water use, initial conditions, and hydraulic properties. GSFLOW then calculates hydraulic heads at discrete points (nodes in a model cell) and flows within the model domain (Ely and Kahle, 2012). For the Laurel Hill Creek Basin, there were a limited number of discrete points available for calibration during the model calibration period due to the availability of a small number of water-level measurements for groundwater wells.

PRMS Overview

PRMS is a modular, deterministic, distributed-parameter, physical-process basin model used to simulate and evaluate the effects of various combinations of precipitation, climate, and land use on basin response (Markstrom and others, 2008). A response to precipitation and hydrologic characteristics that route water through the basin is a function of the temporal and spatial variability of hydrologic parameters, water sources and sinks, and storage in a basin. Simulated results include water-balance, snow dynamics, streamflow, surface runoff, interflow, and groundwater recharge. PRMS distributes water from the top of the plant canopy to the bottom of the soil zone on the basis of physical characteristics of the landscape and the interaction of these characteristics with hydrologic processes. Physical characteristics of the landscape need to be defined in PRMS, along with climatic variables that dictate the movement of precipitated water through the top layer of the system, defined here as the plant canopy down to the rooting zone. The PRMS model is partitioned into specific modules that are linked together in the model to move water through the system. These modules are designed to compartmentalize the basin into a series of interconnected reservoirs (fig. 13).

The soil-zone reservoir is divided into three finite-volume reservoirs: the capillary reservoir, gravity reservoir, and preferential-flow reservoir. These finite-volume reservoirs were developed in PRMS to allow for saturation excess in the soil zone to become Dunnian surface runoff. Dunnian surface runoff is surface runoff that occurs when soil saturation is exceeded (Markstrom and others, 2008). The capillary reservoir represents water held in the soil by capillary forces between the wilting and field-capacity thresholds. Water is removed from the reservoir by evaporation and transpiration, or the water can flow to the gravity reservoir. The gravity reservoir represents water in the soil zone between field-capacity and saturation thresholds that is not subject to the preferential-flow threshold. The gravity reservoir is capable of receiving groundwater discharge into the soil zone whenever the groundwater head in a connected finite-difference cell is greater than the soil-zone base. Gravity drainage is added to the groundwater reservoir in PRMS when using the PRMS-only mode in GSFLOW, whereas for the coupled model, the gravity drainage goes to MODFLOW finite-difference cells. The groundwater reservoir in PRMS can discharge water only to a stream, a downslope groundwater reservoir, and (or) a groundwater sink. Thus, the gravity reservoir is not capable of receiving groundwater discharge when using the PRMS-only mode. Water in the gravity reservoir is available for downslope flow (slow interflow) within the soil zone.

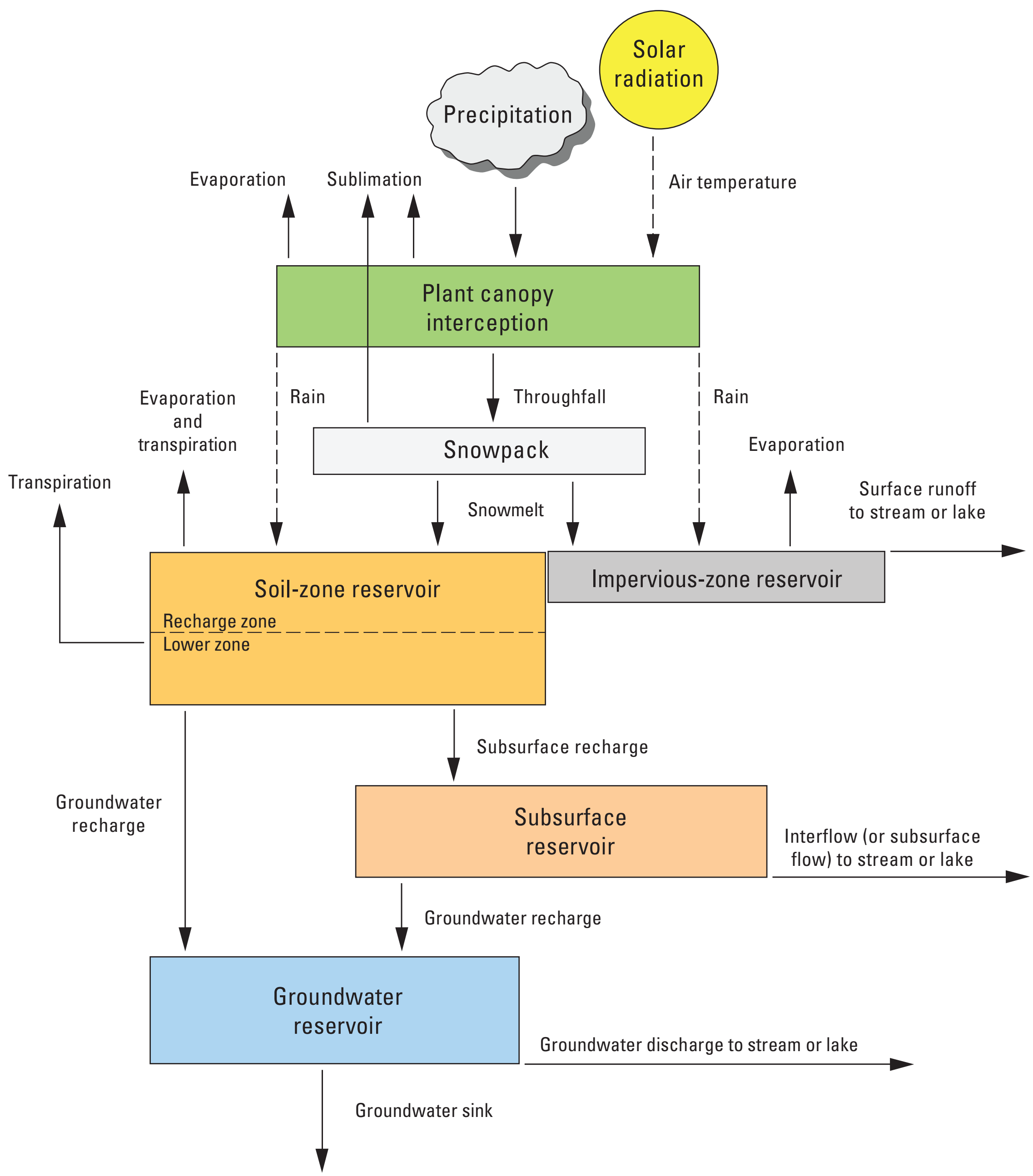


Figure 13. The Precipitation-Runoff Modeling System. (Modified from Leavesley and others, 1983)

The preferential-flow reservoir represents soil water between field capacity and saturation that is available for fast interflow through relatively large openings in the soil of each Hydrologic Response Unit (HRU) (Markstrom and others, 2008). Saturation excess in the preferential flow reservoir is available for Dunnian runoff. The soil-zone reservoir is the reservoir from which fast and slow interflow occur; this reservoir also provides recharge to the groundwater reservoir. Water that is not stored in the groundwater reservoir either is discharged to a stream or lake or goes to a groundwater sink. For the Laurel Hill Creek model, no water was diverted to either a groundwater sink or a lake.

Different modules are available within PRMS to parameterize the model (Markstrom and others, 2008). The modules selected primarily depend on the data available for input and the specific purpose for which the model is constructed.

Basin Delineation

The boundaries of the basin used for PRMS model development were defined by overlaying the actual basin boundary, generated by the USGS StreamStats program (U.S. Geological Survey, 2012) as defined by topographic characteristics, with the MODFLOW grid. This created an irregular, jagged basin boundary because it was essential that the PRMS and MODFLOW boundaries align for the coupled model. MODFLOW cells were 150 m by 150 m in size; smoothing the boundary to match the actual basin boundary was not an option. Aligning the PRMS boundary with the MODFLOW boundary gave a total watershed area of 79,567.34 acres (127.3 mi^2), a size that exceeded the actual watershed area by 2 mi^2.

Digital Elevation Model

A digital elevation model (DEM) was generated for use in the PRMS model using the 30-m grid USGS National Elevation Dataset (NED) (U.S. Geological Survey, 2009b). The DEM was enhanced by overlaying the 30-m grid on a10-m grid, then processed using methods described by Viger and Leavesley (2007). The higher resolution elevation data were used to more accurately simulate runoff characteristics in the basin, better define slope and aspect parameters, and better determine the spatial distribution of form of precipitation for precipitation events that occurred when events could be either rain or snow.

Stream Network

Elevations were combined with the USGS National Hydrography Dataset (NHD) (U.S. Geological Survey, 2009a) to incorporate known stream locations into the DEM prior to establishing the modeled area in PRMS. The stream network that is created is broken into stream segments. The streamflow-routing package (SFR2) in MODFLOW creates stream reaches. Stream reaches are stream segments located within specific MODFLOW cells. There can be multiple stream reaches in any one MODFLOW cell, but each stream reach can be associated with only one MODFLOW cell. These stream reaches are input to PRMS so that the stream network defined in PRMS is broken into reaches. Surface runoff and interflow generated in PRMS are added to stream reaches using a PRMS cascade module that routes water from upland areas to stream reaches. The stream network in PRMS included a buffered area around the stream to optimize the exchange of surface water and groundwater with the stream channel.

Generation of Hydrologic Response Units

PRMS simulations are based on physical laws, empirical relations, and associated parameters and attributes of the modeled area. Because these parameters vary spatially and temporally, each basin in a PRMS model is partitioned into a series of hydrologic response units (HRUs). The discretization can be based on hydrologic and physical characteristics such as drainage boundaries, land-surface elevation, slope, and aspect; plant type and cover; land use; distribution of precipitation, temperature, and solar radiation; soil morphology and geology; and flow direction. Each HRU is assumed to be homogeneous with respect to these hydrologic and physical characteristics and to its hydrologic response. A water balance and an energy balance are computed daily for each HRU (Markstrom and others, 2008). For the Laurel Hill Creek Basin, the geographic information system (GIS) Weasel created by Viger and Leavesley (2007) was used to delineate two-plane HRUs throughout the basin. The DEM is input to the GIS Weasel, and the Weasel delineates a drainage network on the basis of the elevation of the Area of Interest (Viger and Leavesley, 2007). The GIS Weasel software uses a graphical user interface built upon a computing platform of Workstation Arcinfo GIS (ESRI Inc., 2001). The two-plane approach creates HRUs on either side of a stream segment, and upland areas that drain to the downgradient HRUs are separate from the HRUs delineated along stream channels. The area immediately adjacent to the stream was designated as a separate HRU. These HRUs immediately along the stream channel were defined as stream-buffer HRUs and varied in width (from the center line of the stream) from 0 to 200 meters. In general, HRU generation for the basin was dictated primarily by the drainage network. Other physical characteristics that were incorporated into HRU development were changes in slope and land use. Once the physical boundaries of the HRUs are finalized in the GIS Weasel, these characteristics are numerically defined in the PRMS parameter file.

Climate and Streamflow Data

Daily values for climate and streamflow are input to PRMS in a file called the PRMS data file. Climatic data input to PRMS must include maximum and minimum air temperatures, precipitation amounts, and solar radiation data. Pan evaporation data can also be input, but this was not included for the Laurel Hill Creek Basin model. The climate data for the closest available continuous recording stations should be input to the model. Large gaps of missing data can be problematic, so it is necessary to screen the climate data so that stations with more than 10 percent of missing daily values are excluded from the input data file. Solar radiation data are typically limited, so the best approach is to use the nearest airport location that has daily solar radiation data available. For both precipitation and temperature data, three different modules are available to distribute temperatures and precipitation across the basin that is being modeled.

Daily observed values for streamflow need to be entered into the PRMS data file so that the modeled results can be compared to actual data. There should be no missing data in the streamflow record. Data from more than one streamflow station can be input to PRMS, and simulations can be generated for comparison to these various stations; however, for the Laurel Hill Creek Basin, only one streamflow-gaging station was used (USGS station 03080000 Laurel Hill Creek at Ursina, Pa.).

Model Parameterization

Parameters input to PRMS are necessary in order to derive simulated values for streamflow. The number of values for each parameter is dictated by the dimension of that particular parameter. Dimensions define the number of spatial features and constants, such as the number of HRUs, number of months in a year, and the number of temperature stations (Markstrom and others, 2008). Some dimensions are one array; others are two arrays. For example, the parameter summer canopy density is a one-dimensional array that has one value for each HRU. The dimension for summer canopy density is nhru. An example of a two-dimensional array is a precipitation parameter (rain_mon) that has monthly values and is distributed across each HRU. This two-dimensional parameter has 12 values for each HRU (nmonth x nhru).

PRMS has distributed and non-distributed parameters (Ely and Kahle, 2012). Distributed parameters are attributed to each HRU and describe physiographic characteristics, such as area, slope, canopy density, and soil characteristics. Other distributed parameters are those that describe hydrologic processes such as subsurface flow and climatic variables that can be adjusted by HRU on the basis of physical characteristics of the HRU. Non-distributed parameters are parameters held constant throughout the basin (these parameters have a dimension equal to one), such as the parameter *tmax_allsnow*, which is defined as the “monthly maximum air temperature at which precipitation is all snow” (Markstorm and others, 2008).

Parameters with discrete spatial features that have distinct values for each HRU were derived by compiling geospatial databases for the basin, then applying tools in ARCMAP 9.2 (ESRI Inc., 2009) to spatially distribute the data by HRU. The types of geospatial data that were input include those physiographic characteristics listed above, plus others such as vegetative-cover type, land use, and aspect. Land-use and vegetative-cover-type data were derived from the 2001 National Land Cover Database (Multi-Resolution Land Characteristics Consortium 2001). Soil characteristics were compiled from the SSURGO database for the three different counties that encompass the basin: Somerset, Westmoreland, and Fayette (U.S. Department of Agriculture, Natural Resource Conservation Service, 2004a, 2004b, 2006). The hydrology and elevation datasets were described previously. Once distributed to each HRU, the geospatial data from these various datasets were reclassified, when necessary, to conform to acceptable ranges that are needed to run the PRMS model. Various techniques were used for the reclassification with some of the details for this described in Viger and Leavesley (2007). Viger and Leavesley (2007) developed the GIS Weasel to aid in the preparation of spatial data for input to hydrologic models. The GIS Weasel was used for this study to generate parameter values. It was also used as a guide for parameterization derived by other methods. All parameters used in the PRMS only mode of the GSFLOW model are described in Markstrom and others (2008); much of this information was derived initially from the original PRMS manual (Leavesley and others, 1983).

GSFLOW Coupling of PRMS and MODFLOW

After flow models for PRMS and MODFLOW had been calibrated separately (uncoupled), GSFLOW was used to couple the two models. The GSFLOW model can be run in three different modes: PRMS only, MODFLOW only, and a coupled model. The version of GSFLOW used for the Laurel Hill Creek model was run in the PRMS- and MODFLOW-only modes until PRMS and MODFLOW were calibrated to observed conditions.

Prior to coupling the PRMS and MODFLOW models, a recharge array from PRMS was output and used as input to the MODFLOW model. The models were then coupled. A critical aspect of the coupled model is the linking of the HRUs developed for PRMS with the finite-difference cells in MODFLOW. This linkage is primarily done through the application of gravity reservoirs that transfer water from the HRUs to the finite-difference cells (Markstrom and others, 2008). Once coupled, the PRMS groundwater reservoir is replaced by MODFLOW components.

The movement of water from PRMS HRUs to finite-difference cells is simulated in the Unsaturated-Zone Flow (UZF) Package within MODFLOW (Niswonger and others, 2006). Flow in the unsaturated zone beneath the soil zone and water bodies is based on a one-dimensional kinematic wave approximation. Above the soil and water body zone, hydrologic processes are defined by PRMS. Once the water is routed through the unsaturated zone, hydrologic processes are defined by MODFLOW. It is worth noting that the simulated routing of water in the coupled GSFLOW model is conducted through the Streamflow Routing Package within MODFLOW (Niswonger and Prudic, 2005).

Characterization of Water Quality and Quantity

The quality and quantity of water in the Laurel Hill Creek Basin were characterized for low-flow conditions in 2007 and compared to criteria for HQ-CWF waters. Physical attributes of the basin were acquired and stored into GIS layers for the basin. All the water-quality data collected for this project in 2007, along with the stream temperature data collected from 2007–10, are available at the USGS National Water Information System (NWIS) website (http://dx.doi.org/10.5066/F7P55KJN). In addition, hydrologic (primarily from the continuous streamflow-gaging station on Laurel Hill Creek at Ursina, Pa.) and water-use data available for the basin were compiled. The field data, GIS data, and water data were used to develop a GSFLOW model for the entire basin.

Water Quality

The PaDEP has published specific chemical and thermal criteria for a HQ-CWF. To meet HQ-CWF criteria, the stream temperature must not exceed a maximum of 3.3 °C for January and February to 18.9 °C for July and August (appendix 2), the DO concentration must be greater than or equal to 5.0 mg/L, the pH must be 6.0 to 9.0 inclusive, and the concentration of ammonia must not exceed established toxicity thresholds (Commonwealth of Pennsylvania, 2009). The EPA (2015a) has also published nationally recommended water-quality criteria for aquatic life that are somewhat broader in range and include more constituents than the PaDEP criteria. The EPA water-quality criteria give a range of concentrations, based on acute and chronic impacts to aquatic life. Chronic impacts to aquatic life can occur if pH is less than 6.5 or greater than 9.0, if Al (given a pH range of 6.5–9.0) exceeds 87 µg/L, if Cl exceeds 230 mg/L, or if Fe exceeds 1,000 µg/L. Additionally, nutrient water-quality criteria proposed by the EPA (2000) for streams in Ecoregion XI (Central and Eastern Forested Uplands), which includes the Laurel Highlands, could be applicable to minimize nutrient enrichment and eutrophication. The proposed nutrient criteria for total N and total P are 0.31 mg/L and 0.01 mg/L, respectively, for streams (U.S. Environmental Protection Agency, 2000).

Human water use in the basin necessitates withdrawals from groundwater and surface-water sources; therefore, the water chemistry of both groundwater and surface water is an important attribute of water for human consumption, for which drinking water standards could be relevant. The EPA (2012) has published drinking water standards for maximum contaminant levels (MCLs) and SMCLs for many constituents relevant to this study. MCLs have been established for As (4 µg/L), NO_3 (10 mg/L as N), and NO_2 (1 mg/L as N). SMCLs have been established for Al (50 to 200 µg/L), Cl (250 mg/L), Fe (300 µg/L), Mn (50 µg/L), pH (6.5 to 8.5 inclusive), and SO_4 (250 mg/L). The MCL for NO_3 and the SMCLs for Cl, Fe, and SO_4 are exactly the same as the levels established by the Commonwealth of Pennsylvania (2009) for potable water supplies (PWS). The Mn level for a PWS in Pennsylvania is 1,000 µg/L.

Chemistry of Surface Water

Results of analyses of surface-water samples collected in summer and fall 2007 indicate that low-flow water quality was affected by land-use practices and by geologic and hydrologic factors. Due to the proximity to various sources or activities that affect water quality on the local scale, tributaries usually showed a wider range of constituent values than the main stem of Laurel Hill Creek.

The chemical criteria published by PaDEP indicated that only one main-stem site did not meet the criteria for a HQ-CWF. The uppermost site sampled in the main stem (LHC-1st, station 03079320) had a measured DO of 3.4 mg/L, which is below the 5.0 mg/L minimum criteria for DO concentrations. This station also had the highest measured ammonia-N concentration (0.192 mg/L) for all sites sampled, but this met the ammonia criteria as established by PaDEP (Commonwealth of Pennsylvania, 2009). All the main-stem sites met the EPA guidelines for nationally recommended water-quality criteria.

Total-N concentrations in the main stem ranged from 0.35 to 1.42 mg/L (fig. 14, appendix 1), with highest values associated with agricultural land use in the northeastern part of the basin. Thus, all the main stem samples exceeded the relevant nutrient criterion for total N concentration of 0.31 mg/L in streams (U.S. Environmental Protection Agency, 2000). The data show that total N concentrations for the main stem are highest in the upper part of the basin. The highest total N concentration (1.42 mg/L) for the main stem was measured at LHC-1st (station 03079320) (fig. 14; appendix 1); the second highest (1.2 mg/L) and third highest (1.17 mg/L) concentrations of total N were measured at LHC-A3 (station 03079550) (fig. 8), also in the upper part of the basin. The total P concentrations along the main stem ranged from 0.01 mg/L (in some cases, less than (<) 0.02) to 0.06 mg/L (appendix 1). The highest total P concentration (0.06 mg/L) measured along the main stem was also at LHC-1st (station 03079320). All samples in the upper reaches of the main stem had total P concentrations of 0.01 or greater, which exceeded or equaled the nutrient criteria of 0.01 mg/L in streams (U.S. Environmental Protection Agency, 2000). Water-quality data collected for the Rivers Conservation Plan (RCP) in 2003 also showed the highest nutrient concentrations in the main stem in the upper part of the basin (Crouse & Company of Somerset and Kleinschmidt Group, 2005). These results are, in general, consistent with the PaDEP (2011) designation of the upper section of the main stem on the 303(d) list of impaired stream segments in Pennsylvania.

The only constituent measured for surface-water samples collected in the main stem of Laurel Hill Creek that had values exceeding the EPA MCL, EPA SMCL, or PaDEP PWS

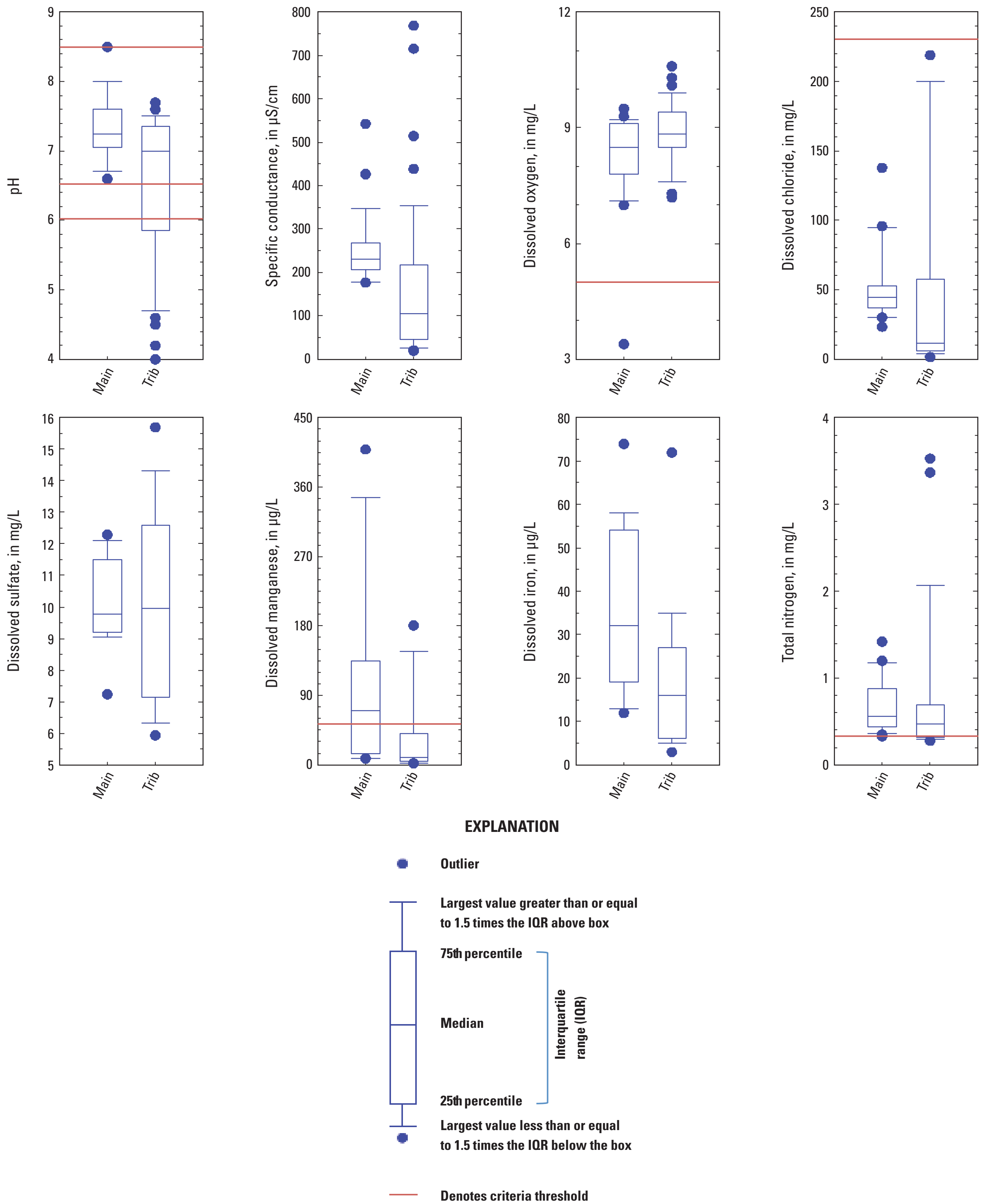


Figure 14. Distribution of selected water-quality constituents in surface-water samples collected at main stem and tributary sites in the Laurel Hill Creek Basin, southwestern, Pennsylvania, 2007. (µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; µg/L, micrograms per liter; Main, main stem of Laurel Hill Creek; Trib, tributary stream to Laurel Hill Creek)

criteria was Mn (fig. 14). Concentrations of Mn greater than the SMCL can cause black oxide staining of ceramic plumbing fixtures and other light-colored materials. Fifty-six percent of the Mn samples collected in the main stem exceeded the SMCL of 50 µg/L. The highest Mn concentration was measured at LHC-1st (409 µg/L), which is the upper-most site sampled on the main stem. Mn concentrations gradually decreased along the main stem with mean concentrations at LHC-U (the furthest downstream site) about 14 µg/L (appendix 1).

The chemical criteria published by PaDEP indicate that some of the tributary sites did not meet the criteria of a HQ-CWF. The values for seven tributaries had pH values less than the 6.0 criteria (appendix 1). These tributaries were generally located in the western half of the basin in drainage areas that are completely forested. All tributary sites did meet the PaDEP CWF criteria, based on DO and ammonia concentrations. An additional three tributaries had pH values between 6.0 and 6.5 (appendix 1), indicating that these tributaries did not meet the EPA criteria for aquatic life. All tributaries sampled met the EPA aquatic criteria pertaining to Al, Cl, and Fe.

Nutrient concentrations for some tributary sites in the Laurel Hill Creek Basin also exceeded the relevant nutrient criteria (fig. 14), with the highest concentrations in samples downstream from wastewater discharges. The highest total N for tributary sites was measured at station 03079480 on Kooser Run (3.31 and 3.46 mg/L) (appendix 1), and is more than 10 times greater than the relevant total N nutrient criteria (U.S. Environmental Protection Agency, 2000). A wastewater treatment facility, along with a fish hatchery in the upper part of Kooser Run subbasin, could be the sources of the elevated N. The only other tributary subbasin with a measured total N concentration greater than 1 mg/L was Lost Creek (station 03079740) with a measured total N concentration of 2.07 mg/L in June 2007. A campground located in the Lost Creek Basin discharges treated wastewater into the creek upstream from the sampling site. The concentration of total P measured for Lost Creek (0.11 mg/L) in June 2007 was the highest measured total-P concentration in the entire Laurel Hill Creek Basin (appendix 1) and was also more than 10 times greater than the relevant total P nutrient criteria (U.S. Environmental Protection Agency, 2000). Kooser Run and Lost Creek also were found to have relatively high nutrient concentrations for samples collected for the RCP (Crouse & Company of Somerset and Kleinschmidt Group, 2005). Note that Crab Run (station 03079350) (fig. 8), a tributary in the upper part of Laurel Hill Creek Basin within an area of concentrated agricultural activity, was not sampled for nutrients because of inaccessibility.

None of the tributaries exceeded any MCLs for the constituents sampled, but SMCLs were exceeded for many tributary sites. As stated earlier, 10 tributary sites were below the EPA water-quality criteria for pH of 6.5. The lower pH limit for the SMCL is also 6.5. Three of the 16 samples collected at tributary sites had Mn concentrations greater than the SMCL of 50 µg/L. Two of these samples that exceeded the SMCL for Mn (181 and 147 µg/L) were collected at Cranberry Glade Run (station 03079480). This tributary drains a boggy lake and had measured pH values of 4.5 and 4.8. Low DO conditions such as those in a boggy lake help to extract Mn from organic-rich sediments; in addition, Mn solubility increases with decreasing pH (Hem, 1985). The low pH of Cranberry Glade Run directly contributed to the elevated Al concentrations of 442 and 476 µg/L. This site was the only tributary to exceed the SMCL for Al of 200 µg/L (appendix 1). None of the tributary sites exceeded the levels established by the Commonwealth of Pennsylvania (2009) for PWS.

Even though Cl concentrations were below the water-quality and PWS criteria established by the EPA and the Commonwealth of Pennsylvania, Cl concentrations in the upper parts of the basin were elevated in one tributary sampled and the main stem. The highest Cl concentrations in the Laurel Hill Creek Basin were measured in a tributary subbasin. Two surface-water sites sampled, Clear Run (station 03079400) and Crab Run (station 03079350), are transected by the Pennsylvania Turnpike (I-76) where they flow in a general north to south direction and feed into the main stem of Laurel Hill Creek (fig. 8). Concentrations of Cl for Clear Run (station 03079400) below I-76 were 219 and 200 mg/L for samples collected in June and September 2007, respectively (fig. 15; appendix 1). The Cl concentration measured in Clear Run for the RCP was 190 mg/L (Crouse & Company of Somerset and Kleinschmidt Group, 2005). The corresponding sodium (Na) concentration of 118 mg/L in June 2007 and SC values of 769 and 716 microsiemens per centimeter at 25 degrees Celsius (µS/cm) for Clear Run in June and September 2007 also were higher than for any other sites sampled (appendix 1). Samples for Cl and Na were not collected at Crab Run (station 03079350), but the SC for Crab Run was measured at 515 µS/cm at 25 °C (fourth highest SC measured in the Laurel Hill Creek Basin) (appendix 1). The high values for SC in these tributaries contributed to the high values recorded downstream along the main stem (fig. 16). The highest mean Cl (117 mg/L), Na (77 mg/L), and SC values (485 µS/cm at 25 °C) recorded in the main stem were for the site (LHC-A0-2, station 03079420) immediately below the confluence with Clear Run. The likely cause of the elevated Cl, Na, and SC values is the application of road deicing salts (NaCl) on I-76. Deicing materials have been documented as causes of elevated concentrations of dissolved salts in shallow groundwater and soils (Jones and Sroka, 1997); eventually, the salt constituents can run off the roadway to the surface-water system. The influx of Cl, Na, and other dissolved constituents in the upper parts of the basin causes a gradient of higher to lower values for specific conductance moving downstream through the basin until Laurel Hill Creek discharges into the Casselman River. The lowest mean SC (186 µS/cm at 25 °C) value for the main stem occurred at LHC-U (station 03080000), the farthest downstream sampling site (fig. 8). The lowest mean Cl concentrations for the main stem downstream from the confluence of Clear Run and Laurel Hill Creek occurred at the three farthest

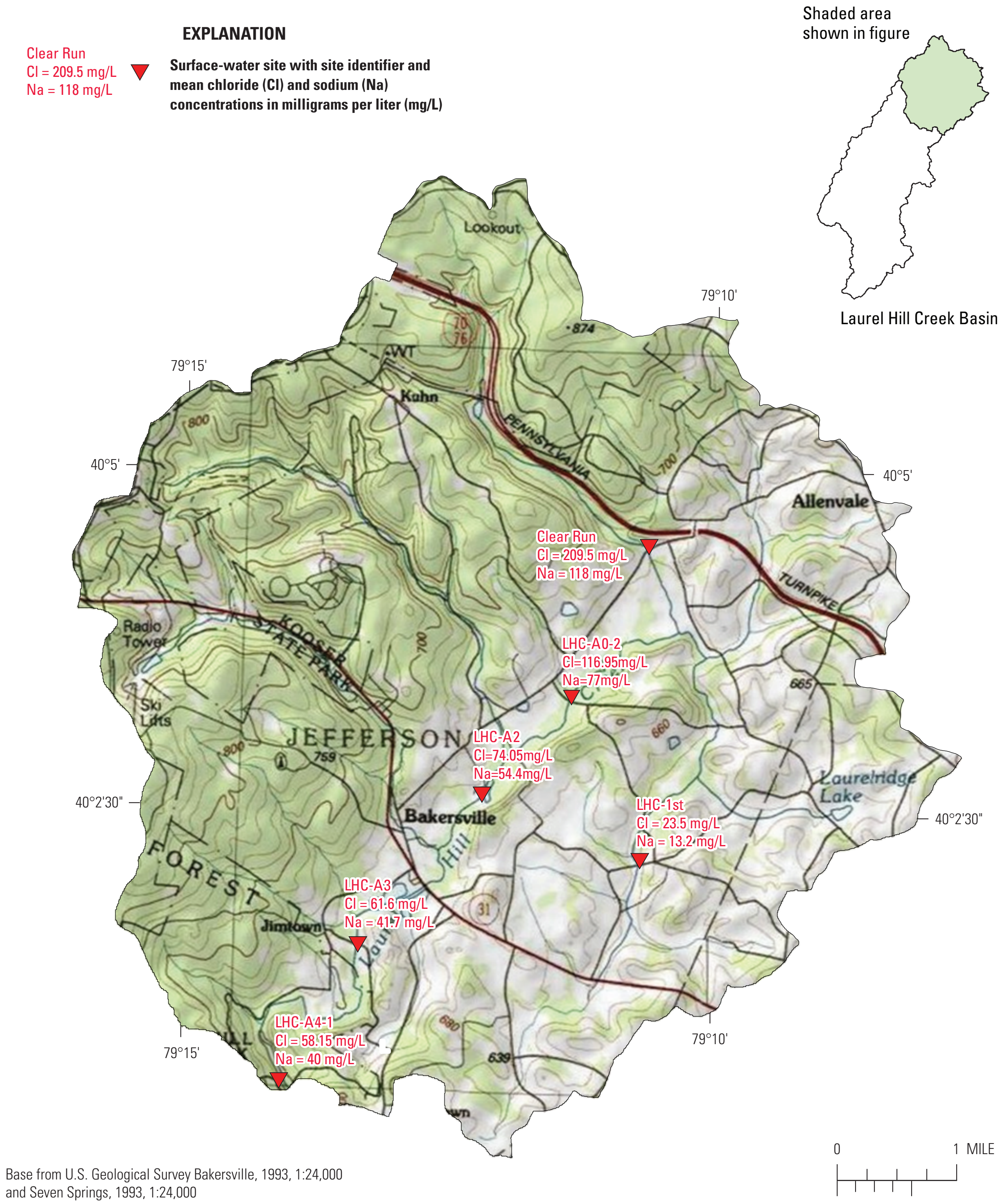


Figure 15. Chloride and sodium concentrations measured in the upper part of the Laurel Hill Creek Basin, southwestern, Pennsylvania, 2007.

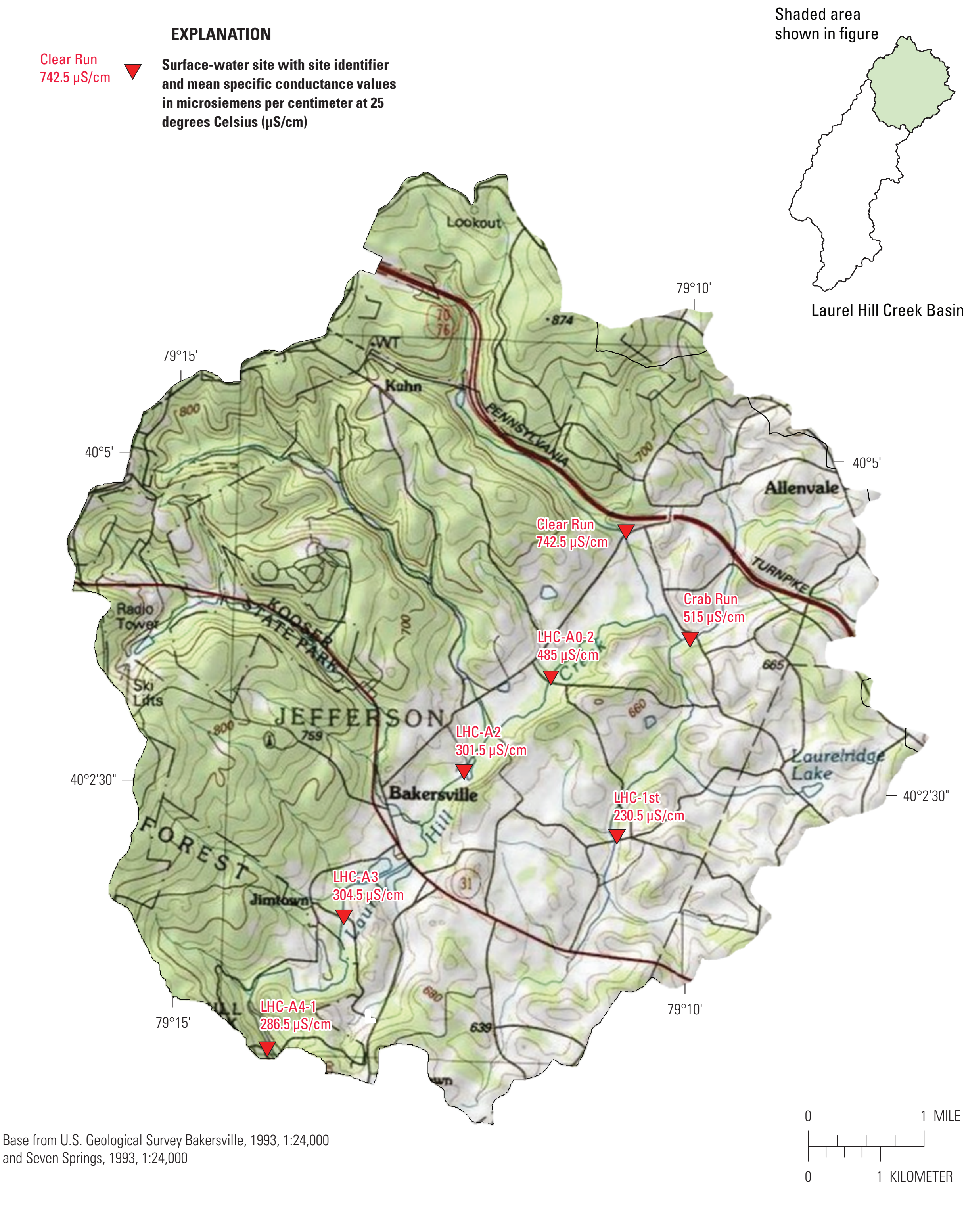


Figure 16. Specific conductance values measured in the upper part of the Laurel Hill Creek Basin, southwestern, Pennsylvania, 2007.

downstream sampling sites, LHC-A8 (station 03079942), LHC-A9 (station 03079993), and LHC-U (station 03080000) (fig. 8), with Cl concentrations at these sites ranging from 34.45 to 35.1 mg/L (appendix 1). The lowest Cl, Na, and SC values measured in the basin were for tributary subbasins not affected by road runoff. Eight tributary sites had Cl concentrations of less than (<)10 mg/L (fig. 14). The lowest SC values were measured at tributary sites Buck Run (station 03079580, 20 µS/cm at 25 °C), Garys Run (station 03079700, 26 µS/cm at 25 °C), and Cole Run (station 03079704, 26 µS/cm at 25 °C). These sites are in the central part of the basin and drain forest-covered ridges along the western boundary (fig. 8).

The signature of geologic formations on water quality is apparent only for the Laurel Hill Creek Basin tributary sites because various units contribute water to the main stem of Laurel Hill Creek. Sharpe and others (1984) showed that acidic pH values were common along Laurel Hill owing to inputs of acidic precipitation along with the poor buffer capacity of certain geologic units. The lowest pH values in the basin were measured for tributary sites, namely Crise Run (station 03079540, 4.1), Cole Run (station 03079704, 4.6), and Gross Run (station 03079520, 4.95), which drain the forested western ridge and are underlain by the Allegheny Formation. Some tributary sites underlain by the Pottsville Formation had mean pH values of <6.0, including Cranberry Glade Run (station 03079900, 4.65) and Moore Run (station 030794464, 5.85). The low pH values for Cole and Cranberry Glade Runs were also measured in water-quality samples collected for the RCP report (Crouse & Company of Somerset and Kleinschmidt Group, 2005). Note that the water-quality samples collected from Cranberry Glade Run were collected downstream from Cranberry Glade Lake. The main-stem sites sampled in 2007 had a range of mean pH values from 6.6 to 8.5 (appendix 1).

Specific conductance (SC) data for the Laurel Hill Creek Basin tributary sites varied in relation to geologic formation. The lowest SC values for tributary sites were measured for sites underlain by the Mauch Chunk and Pottsville Formations. The median SC values for samples collected in tributaries underlain by the Mauch Chunk and Pottsville Formations were 42 and 44 µS/cm at 25 °C, respectively; the median SC values for the Allegheny and Glenshaw Formations were 134 and 306 µS/cm at 25 °C, respectively. Tributary sites underlain by the Mauch Chunk Formation had lower concentrations for most of the constituents measured. Median concentrations for dissolved sulfate (SO_4), iron Fe, and Mn were 6.1 mg/L, 8.0 µg/L, and 7.7 µg/L, respectively, measured in samples from tributaries underlain by the Mauch Chunk Formation, whereas samples from tributaries underlain by the Allegheny Formation had median concentrations of dissolved SO_4, Fe, and Mn of 11.3 mg/L, 22 µg/L, and 10 µg/L, respectively. Samples from tributaries underlain by the Pottsville Formation had higher median values for dissolved SO_4 and Mn than samples from tributaries underlain by the Mauch Chunk Formation (fig. 17).

Temperature of Surface Water

The stream temperatures measured during the water-quality synoptics indicated that the main stem had elevated stream temperatures relative to tributary sites. The stream temperature maximums for a HQ-CWF, based on PaDEP criteria, are 17.8 and 15.5 °C for the synoptics conducted from June 25–27, 2007, and September 17–19, 2007, respectively. For the 12 main-stem sites sampled, only one (LHC-A0-2, station 03079420, 17.6 °C) had a measured stream temperature below the 17.8 °C maximum for the June synoptic, and nine main-stem sites were below the 15.5 °C maximum for the September synoptic. For the tributary sites, 20 of the 24 sites sampled in June 2007 were below the 17.8 °C maximum, and none of the 20 sites sampled in September 2007 exceeded the 15.5 °C maximum (appendix 1). These data indicate that tributaries in the Laurel Hill Creek Basin meet the thermal criteria for a HQ-CWF in most instances, where as the main stem generally does not meet the thermal criteria. The caveat to the synoptic data is that they represent only instantaneous values.

The daily maximum stream temperatures at the five continuous record sites on the main stem of Laurel Hill Creek from 2007 to 2010 frequently exceeded the HQ-CWF temperature criteria maximum established by the Commonwealth of Pennsylvania (2009). All five sites exceeded the maximum temperature criteria for the summer months in each year. The average maximum temperatures in June ranged from 19.2 °C to 22.0 °C; in July, 20.7 °C to 25.5 °C; and in August, 20.7 °C to 26.0 °C. The stream temperature maximums for a HQ-CWF, based on PaDEP criteria for June, July, and August, are 17.8, 18.9, and 18.9 °C, respectively. The lowest average maximums for these 3 months occurred at the two upper-most stations (03079420 and 03079550), and the highest average maximum occurred at the furthest downstream station (03080100). The five continuous record sites generally did not exceed the HQ-CWF temperature criteria established for the winter months. The percentage of months that exceeded the maximum temperature criteria was lowest for the site furthest upstream (46 percent) and highest for the site furthest downstream (69 percent) (appendix 2).

The network of stream-temperature probes indicated that temperature differences between sites were greater in warmer months than in colder months, with temperatures generally increasing in the downstream direction during warmer months (table 1; appendix 2). The data plotted for July 2008 and February 2009 (fig. 18) show the typical relation between the five stream-temperature monitoring sites. The farthest upstream site is station 03079420 (Laurel Hill Creek below Shanks Run near Bakersville, Pa.) and the farthest downstream site is station 03080100 (Laurel Hill Creek at Ursina, Pa.) (fig. 9). The overall mean stream temperature varied from 10.0 °C at station 03079550 (Laurel Hill Creek at Jimtown near Bakersville) to 12.3 °C for station 03080100. For summer months, the means ranged from 19.1 °C for station 03079420 to 21.5 °C for station 03080100 (table 1). The highest maximum (instantaneous) stream temperatures recorded at the

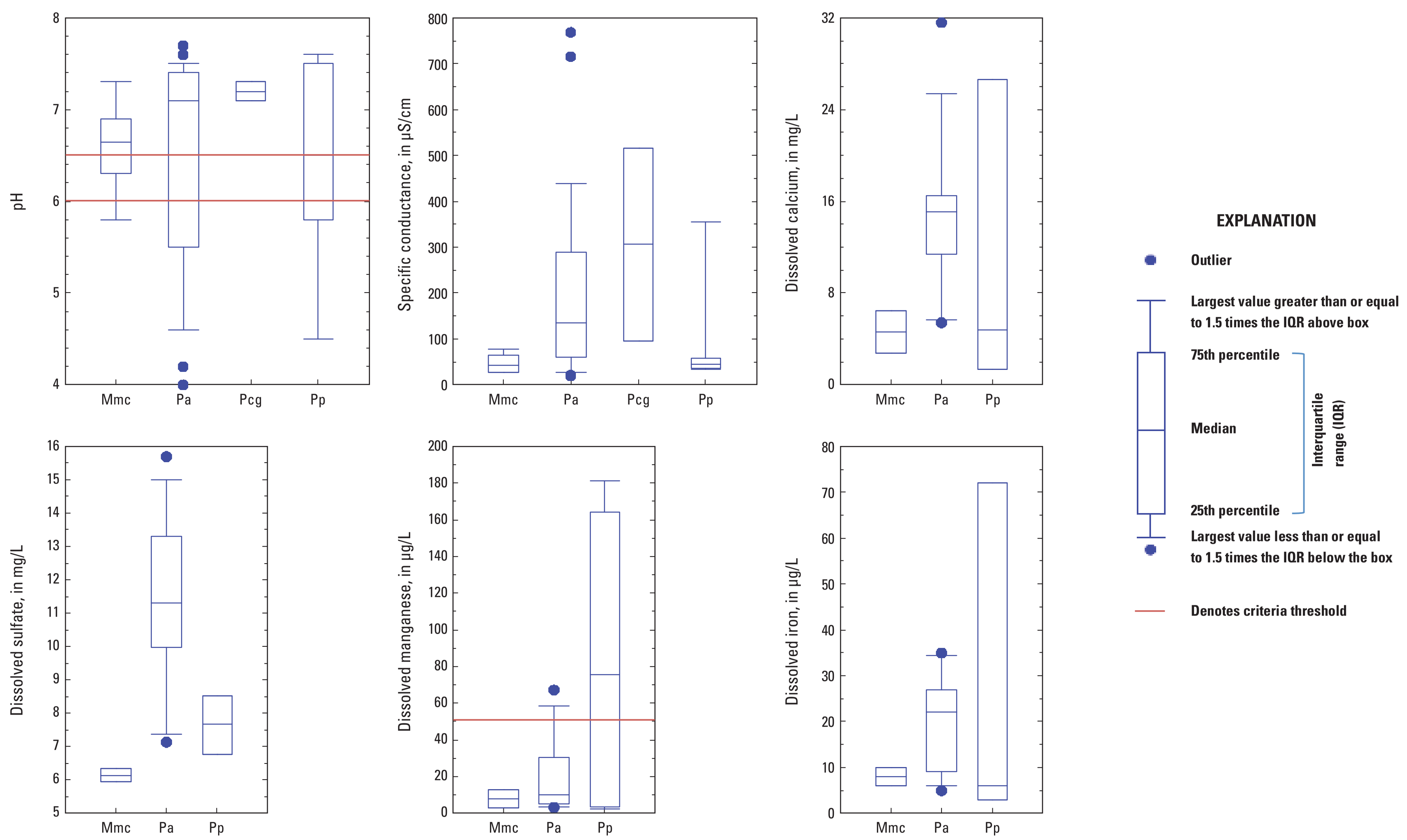


Figure 17. Distribution of selected water-quality constituents, by geologic unit, in surface-water samples collected at tributary sites in the Laurel Hill Creek Basin, southwestern, Pennsylvania, 2007. (Mmc, Mauch Chunk Formation; Pa, Allegheny Formation; Pcg, Glenshaw Formation; Pp, Pottsville Formation; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; µg/L, micrograms per liter)

Table 1. Daily average maximum, minimum, and mean stream temperatures by season at five sites located along the main stem of Laurel Hill Creek, southwestern, Pennsylvania, 2007–10.

[Min, average daily minimum stream temperature in degrees Celsius; Mean, average stream temperature in degrees Celsius; Max, average daily maximum stream temperature in degrees Celsius; Latitude and Longitude in decimal degrees]

Season	Station[1]																			
	03079420				03079550				03079660				03079748				03080100			
	Days	Min	Mean	Max	Days	Min	Mean	Max	Days	Min	Mean	Max	Days	Min	Mean	Max	Days	Min	Mean	Max
Fall	273	10.2	11.0	11.9	273	10.7	11.5	12.3	252	12.0	12.9	13.7	273	10.9	11.9	13.2	252	11.1	13.2	16.0
Winter	271	1.0	1.4	1.9	271	1.2	1.7	2.1	181	1.4	1.8	2.2	271	1.3	1.8	2.3	181	1.2	1.8	2.5
Spring	276	7.6	9.1	10.9	244	7.6	8.8	10.2	184	8.8	9.7	11.0	272	7.8	9.4	11.5	184	8.3	10.1	12.1
Summer	268	17.9	19.1	20.3	230	18.1	19.3	20.4	230	19.8	21.0	22.5	267	18.2	20.0	22.2	230	18.9	21.5	24.8
Overall	1088	9.2	10.1	11.2	1018	9.1	10.0	10.9	847	11.1	12.0	13.1	1083	9.5	10.7	12.3	847	10.5	12.3	14.7

[1]Station	Local name	Station name	Latitude	Longitude
03079420	Duck Pond	Laurel Hill Creek below Shanks Run near Bakersville	40.05583	-79.18917
03079550	Jimtown	Laurel Hill Creek at Jimtown near Bakersville	40.02556	-79.22222
03079660	Triple Creek	Laurel Hill Creek above Crab Run near Barronvale	39.98611	-79.25861
03079748	Whipkey	Laurel Hill Creek at Metzler	39.92	-79.28
03080100	Ursina	Laurel Hill Creek at Ursina near Confluence	39.81556	-79.32944

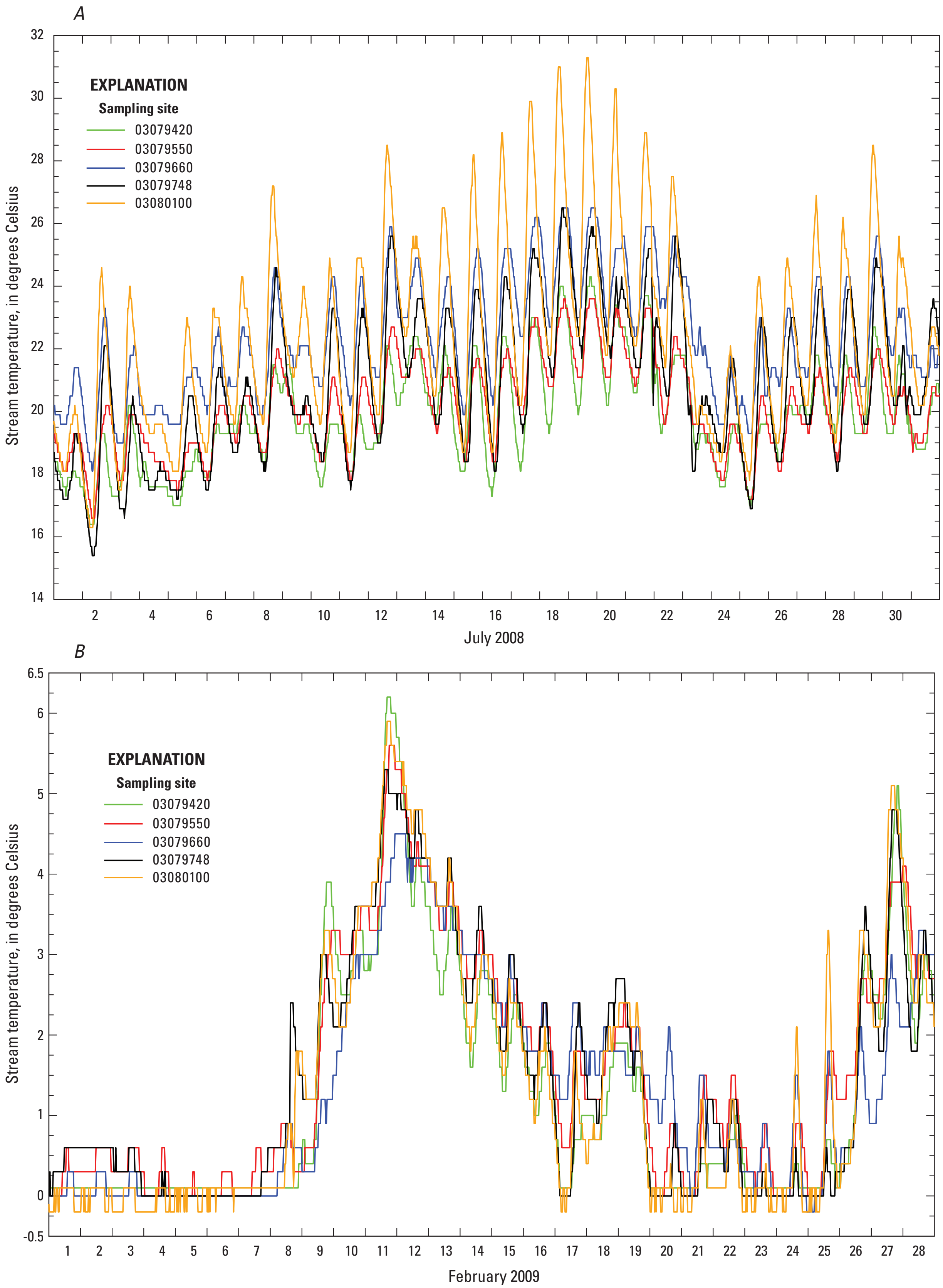


Figure 18. Stream temperatures for *A*, July 2008 and *B*, February 2009 for five sites along the main stem of Laurel Hill Creek, southwestern, Pennsylvania.

five stations ranged from 27.2 °C (August 3, 2007) at station 03079660 to 32.8 °C (July 31, 2007) at station 03080100, both during low-flow conditions. The streamflow for Laurel Hill Creek at Ursina (station 03080000) for August 3, 2007, and July 31, 2007, were 4.0 and 11 cubic feet per second (ft^3/s), respectively (appendix 3). The flow distribution at station 03080000 for the entire period when the stream temperature probes were deployed (July 17, 2007–July 8, 2010) indicates that streamflows of 4 and 11 ft^3/s were in the bottom 1 percent; that is, daily streamflow at station 03080000 was higher than 11 ft^3/s for about 99 percent of the days over the approximately 3-year period.

During winter months, there was a range of only 0.4 °C in average minimum and a range of 0.6 °C in average maximum stream temperatures among sites (table 1). The average minimum stream temperatures ranged from 1.0 °C (station 03079420) to 1.4 °C (station 03079660), whereas the average maximum temperatures ranged from 1.9 °C (station 03079420) to 2.5 °C (station 03080100). Similar to the summer months, the lowest stream temperatures were measured in the upper part of the basin at Duck Pond Road (station 03079420).

Chemistry of Groundwater

Results of analyses of groundwater (wells and springs) samples collected in summer–fall 2007 indicate that water quality was somewhat affected by land use, although the main control on the quality of water was the bedrock formation contributing water to the well or spring. Water-quality samples were collected from six different geologic formations. The Loyalhanna Limestone Formation is the only formation in the basin that was not sampled, and only one well (two samples) within the Casselman Formation was sampled (appendix 4). Well depths ranged from 42 to 410 ft for 18 of 19 wells for which depth data were available; average well depth is about 150 ft (appendix 4).

For the seven geologic formations that are present in the basin, the Mauch Chunk Formation has historically been identified as the best unit for water yields and quality of water. This is reflected in the location of public-supply wells in the basin, all of which are drilled into the Mauch Chunk Formation, which underlies mountainous areas along the western boundary of the basin (fig. 7). MCLs have been established for As (4 µg/L) and NO_3 (10 mg/L as N); neither was exceeded in any groundwater sample collected in the Laurel Hill Creek Basin. The highest concentration for As was 1.30 µg/L (fig. 19), and the highest concentration for nitrate-N was 2.38 mg/L (appendix 4). The highest As concentration was detected in groundwater from a well drilled into the Glenshaw Formation. This same well (SO-874) was the deepest well (410 ft) sampled in the basin, and it had the second highest measured SC (425 µS/cm at 25 °C) of all the wells and springs sampled. The high SC and depth of the well indicate that the high As concentration could be related to the flow path and residence time of the groundwater (Freeze and Cherry, 1979, p.241). Groundwater with longer flow paths and residence times typically is more enriched in dissolved constituents. Eight other groundwater samples were collected from the Glenshaw Formation for As analysis, but only one sample exceeded 0.3 µg/L for As. The other seven concentrations were no greater than 0.12 µg/L (appendix 4). The groundwater sample with the highest nitrate concentration was collected from a spring that is in an agricultural area underlain by the Glenshaw Formation. The three highest (one spring, two wells) nitrate concentrations measured in groundwater (0.79, 1.98, and 2.38 mg/L) were all in samples from sites in agricultural settings underlain by the Glenshaw Formation. Another well sampled in an agricultural setting underlain by the Glenshaw Formation had nitrate-N below the detection level of 0.06 mg/L, indicating that agricultural land use does not necessarily equate to elevated nitrate-N concentrations.

Some groundwater samples exceeded the SMCL values for Fe and Mn. Thirty-four samples were collected for Fe analyses, and 15 of these exceeded the SMCL value of 300 µg/L. Only 1 of 7 samples collected from springs exceeded the SMCL for Fe, whereas 52 percent of the well samples (14 of 27) exceeded the SMCL for Fe. Fe concentrations for springs ranged from nondetect to 303 µg/L (appendix 4; median = 12 µg/L), whereas Fe concentrations for wells ranged from nondetect to 10,400 µg/L (median = 345 µg/L). Thirty-six samples were collected for Mn analyses, and 19 of these exceeded the SMCL value of 50 µg/L. Five of 9 samples collected from springs exceeded the SMCL for Mn, whereas 52 percent of the well samples (14 of 27) exceeded the SMCL for Mn (fig. 19 and appendix 4). Mn values for spring samples ranged from 1 to 157 µg/L (median = 52 µg/L), whereas Mn values in samples from wells ranged from 0.9 to 605 µg/L (median = 69 µg/L). The median DO concentrations for springs and wells sampled were 7.9 and 1.7 mg/L, respectively. It was expected that concentrations of dissolved Mn in samples from springs would be lower than in samples from wells because, at the spring discharge, some Mn would have precipitated out of solution as a result of oxidation. Also, the median SC values for springs and wells were 48 and 198 µS/cm at 25 °C, respectively; therefore, water from springs was generally lower in dissolved solids than well water and this could also be a contributing factor in lower Mn concentrations from springs.

Concentrations of Fe and Mn were somewhat related to geologic unit. Seventy-eight percent of the groundwater samples (wells and springs) collected in areas underlain by the Allegheny Formation exceeded the SMCL for Fe, and 78 percent also exceeded the SMCL for Mn. The highest Fe concentration (10,400 µg/L) was detected in a sample collected from a well within the Allegheny Formation. For groundwater samples collected from the Pottsville Formation, 43 percent exceeded the SMCL for Fe, and 62 percent exceeded the SMCL for Mn. The highest Mn concentration (605 µg/L) was detected in a sample collected from the Pottsville Formation. Only 33 percent of the samples collected from wells within the Mauch Chunk Formation exceeded the SMCL for Fe, and the same was true for Mn. Forty percent of the samples collected from the Glenshaw Formation exceeded the SMCL for Mn, whereas only 11 percent of the samples collected from this formation exceeded the SMCL for Fe (appendix 4; fig. 19). The concentrations of Fe and Mn in groundwater samples were somewhat consistent with the concentrations in samples from tributaries draining these formations. The highest Fe and Mn concentrations for tributaries were detected in samples from tributaries draining the Pottsville Formation (72 and 181 µg/L, respectively). The highest median Fe concentration for tributaries (22 µg/L) was in a surface-water sample from the Allegheny Formation (fig. 17).

Samples analyzed for Al did not exceed or were within the SMCL (range of 50 to 200 µg/L). Al was primarily analyzed in spring-water samples. Two of six samples had concentrations (85.8 and 62 µg/L) within the Al SMCL range (appendix 4). Both of the spring samples that were within the SMCL range for Al were collected in areas underlain by the Pottsville Formation. All other groundwater samples had Al concentrations below 50 µg/L.

None of the groundwater samples exceeded the SMCL or PWS acceptable concentrations for Cl and SO_4 (fig. 19). The highest measured Cl concentration was 73.2 mg/L in well SO-870 completed in the Mauch Chunk Formation. The highest measured SO4 concentration was 166 mg/L in well SO-869 completed in the Pottsville Formation (appendix 4).

Many groundwater samples did not fall within the acceptable range for pH based on the EPA SMCL. Forty-three percent of the groundwater samples collected were either less than pH 6.5 or greater than pH 8.5. Only one groundwater sample exceeded a pH of 8.5; in contrast, 18 samples had pH values below 6.5 (appendix 4). The pH and buffer capacity of groundwater samples are related to geologic formation. The highest median pH values were measured in groundwater samples collected in areas underlain by the Mauch Chunk (median pH, 7.6) and the Casselman (median pH, 7.4) Formations (table 2). The lowest median pH values were measured in groundwater samples collected from the Pottsville (median pH, 5.3) and the Allegheny (median pH, 6.2) Formations. Seventy and sixty percent, respectively, of groundwater samples collected from the Pottsville and Allegheny Formations had pH values less than 6.5. Water with pH values less than 6.5 can cause corrosion problems in water-supply systems (U.S. Environmental Protection Agency, 2015b).

Similarly, the highest median alkalinity value (for a formation with more than two samples collected) was measured in groundwater from the Mauch Chunk Formation [80 mg/L calcium carbonate ($CaCO_3$)], and the lowest median alkalinity values were measured in samples collected from the Pottsville (4 mg/L $CaCO_3$) and Allegheny (38 mg/L $CaCO_3$) Formations (fig. 19). Surface-water samples collected from areas underlain by the Pottsville and Allegheny Formations also showed low pH values relative to other formations.

SC data also showed a relation to geologic unit (fig. 19); however, land use also had some influence. Samples collected in areas underlain by the Pottsville and Allegheny Formations had the lowest median SC values (48 and 106 µS/cm at 25 °C, respectively). All the groundwater samples collected from the Pottsville Formation were from forested areas. The range of SC values for Pottsville Formation samples (10 samples) was 29–130 µS/cm at 25 °C. For samples collected from the Allegheny Formation, the highest SC value (689 µS/cm at 25 °C) was in groundwater from a well (SO-869) located in an agricultural area; however, this well had a nitrate-N concentration of less than 0.06 mg/L. Dissolved Ca, Mg, and SO_4 concentrations for well SO-869 were the highest measured for any groundwater samples. The three highest SC values for all groundwater samples collected were from wells in agricultural areas (appendix 4). The second and third highest SC values were measured in samples from two wells (SO-871 and SO-874) in the Glenshaw Formation. These two wells also had the second and third highest nitrate-N concentrations; however, the relatively high SC was primarily due to elevated concentrations of Ca, Mg, and carbonate.

There were differences in water quality between samples collected from springs and samples collected from wells overlying the same formation. The primary difference is related to the quantity of dissolved ions in the water. As stated by McElroy (2000), total mineralization is lower in springs than in wells because spring water generally circulates in the shallow subsurface, giving a shorter residence time. Higher SC values were observed in well water than in spring water for each geologic formation (table 2). The median SC value for all springs sampled was 48 µS/cm at 25 °C, whereas the median for all wells sampled was 198 µS/cm at 25 °C. The difference in dissolved ions between samples from wells and samples from springs was evident for most constituents. For example, the median Fe and Mn concentrations in water from wells in areas underlain by the Allegheny Formation were 1,970 and 281 µg/L, respectively, and the median Fe and Mn concentrations in water from springs in the same setting were 55 and 91 µg/L, respectively (table 2).

Chemical Relation Between Surface Water and Groundwater

Generally, near-neutral stream samples are present in the main stem of Laurel Hill Creek where groundwater contributions may be increasingly important. Tributary sites had a lower mean pH and alkalinity than the main-stem sites. The mean pH and alkalinity for samples collected in 2007 were 6.5 and 21 mg/L $CaCO_3$, respectively, at tributary sites, and 7.3 and 28 mg/L $CaCO_3$, respectively, at main-stem sites. The average alkalinity in all well samples collected in 2007 was 78 mg/L $CaCO_3$. The groundwater acquires alkalinity by reaction with carbonate minerals. Inflows of groundwater to the main stem added alkalinity to the main stem.

The mean SC for samples collected in 2007 in the main stem (256 µS/cm at 25 °C) was higher than the mean for the tributaries (165 µS/cm at 25 °C), and wells (180 µS/cm at 25 °C). This is reflective of the high dissolved ion input

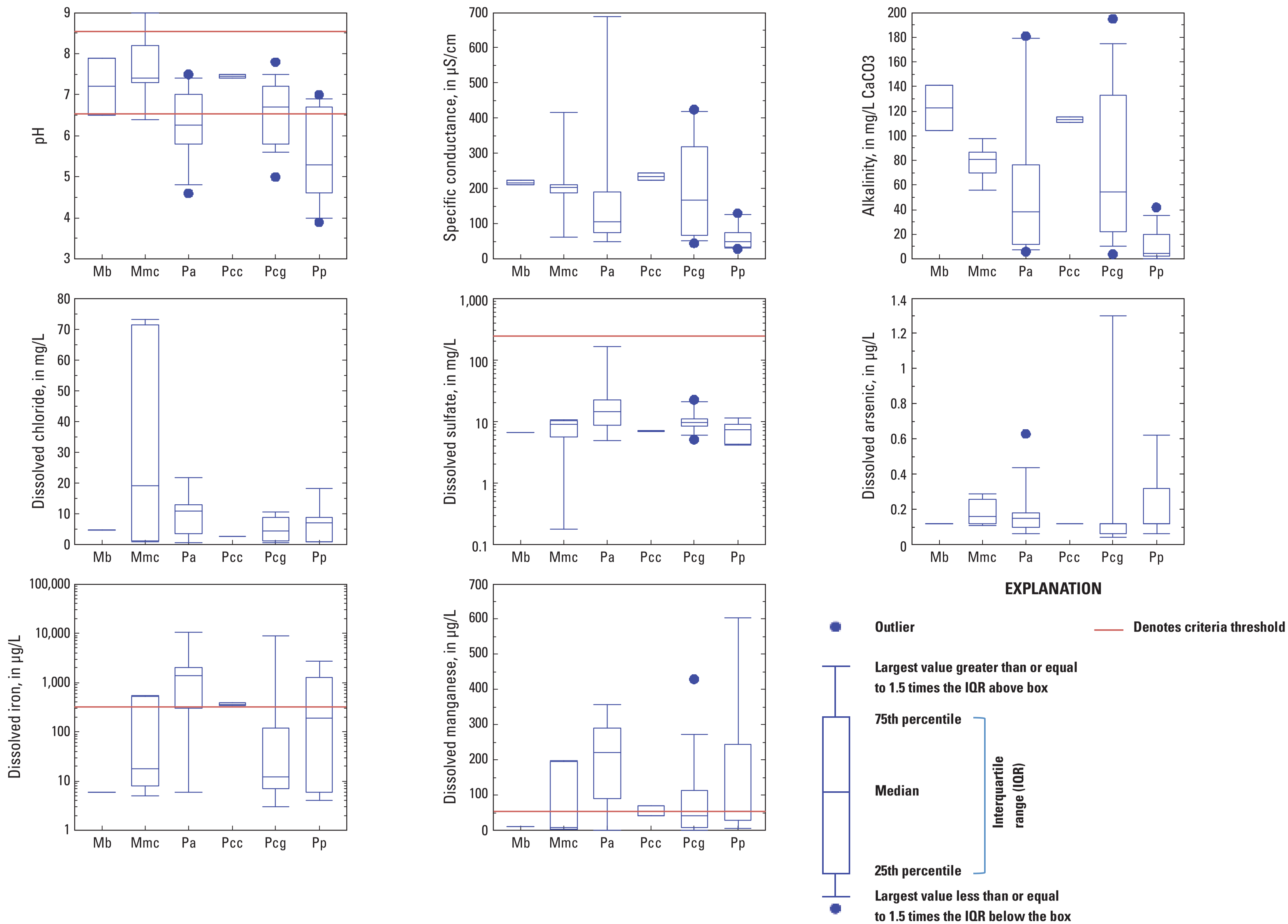


Figure 19. Distribution of selected water-quality constituents, by geologic unit, in groundwater (wells and springs) samples collected in the Laurel Hill Creek Basin, southwestern, Pennsylvania, 2007. (Mb, Burgoon Sandstone; Mmc, Mauch Chunk Formation; Pa, Allegheny Formation; Pcc, Casselman Formation; Pcg, Glenshaw Formation; Pp, Pottsville Formation; $CaCO_3$, calcium carbonate; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; µg/L, micrograms per liter)

Table 2. Median values for specific conductance, pH, iron, and manganese, by geologic formation, for spring and well water samples collected in the Laurel Hill Creek Basin, southwestern, Pennsylvania, 2007.

[NA, not applicable; n, number of observations]

Constituent	Type	Formation											
		Burgoon Sandstone		Mauch Chunk		Allegheny		Casselman		Glenshaw		Pottsville	
		n	Median	n	Median	n	Median	n	Median	n	Median	n	Median
Specific conductance, in microsiemens per centimeter at 25 degrees Celsius	Spring	NA	NA	1	62	3	71	NA	NA	1	45	6	33
	Well	2	217	8	205	6	108	2	234	10	212	4	86
pH, in stardard units	Spring	NA	NA	1	6.4	3	6.8	NA	NA	1	5.0	6	5.0
	Well	2	7.2	8	7.6	7	6.2	2	7.4	10	6.8	4	5.6
Iron, in micrograms per liter	Spring	NA	NA	NA	NA	3	55	NA	NA	1	12	3	6
	Well	1	6	6	18	6	1,970	2	362	8	35	4	968
Manganese, in micrograms per liter	Spring	NA	NA	NA	NA	3	91	NA	NA	1	19	5	52
	Well	1	10	6	6.8	6	281	2	55	9	48	3	432

from Clear Run in the upper part of the Laurel Hill Creek Basin. The Cl concentrations in the main stem of Laurel Hill Creek were elevated as a result of road salt applications.

The main stem in the upper part of the basin and tributary sites receiving wastewater had elevated concentrations of nutrients for samples collected in 2007. The groundwater samples did not indicate any nutrient issues. Both surface water and groundwater had elevated concentrations of Mn greater than the SMCL. The groundwater samples also showed Fe concentrations greater than the SMCL, whereas the surface-water samples were less than the SMCL, primarily owing to precipitation of dissolved Fe in the oxygenated stream environment.

Water Quantity

There are four exceptional value tributaries in the Laurel Hill Creek Basin that are designated high-quality cold-water fisheries. Water quantity is an important issue owing to the significant amount of daily water withdrawals from the basin and because of the importance of the groundwater contribution to streamflow temperature and water quality. Generally, the streamflow at a point is proportional to the upstream drainage area. Drainage area for the tributaries sampled in the Laurel Hill Creek Basin ranged from 0.35 mi^2 for May Run to 12.55 mi^2 for Fall Creek (table 3), with an average drainage area of about 3 mi^2. The drainage area for main-stem sites ranged from 4.36 mi^2 at site LHC-1st (station 03079320) to 121 mi^2 at LHC-U (station 03080000, Ursina, Pa.) (fig. 8; appendix 1).

Characterization of Low Streamflow

Streamflow was measured twice at sites along the main stem of Laurel Hill Creek and most of the tributaries during low-flow periods in June and September 2007 (fig. 8). The measured streamflows were very similar in June and September. The streamflows at tributary sites in June ranged from 0.01 ft^3/s) for May Run (station 03079926) to 2.4 ft^3/s for Jones Mill Run (station 03079640) and Kooser Run (station 03079480, whereas in September, the range was 0.06 ft^3/s for Cole Run (station 03079704) to 2.6 ft^3/s for Jones Mill Run (table 3). For the main stem sites, the range in streamflow in June was 0.1 ft^3/s for LHC-1st (at Lavansville, station 03079320) to 20 ft^3/s at LHC-A9 (near Humbert, station 03079993), whereas for September, the range was 0.47 ft^3/s at LHC-1st to 20 ft^3/s at LHC-U (at Ursina, station 03080000) (table 3). The mean daily discharges computed for station 03080000, based on the continuous stage record for June 25–27, 2007, and September 17–19, 2007, were 16 and 17 ft^3/s, respectively. On the basis of the historical streamflow record for station 03080000 from 1919–2007, a streamflow of 16 cfs is between the 5th and 10th percentile of streamflow for June 25–27, and a streamflow of 17 ft^3/s is between the 25th and 50th percentile of streamflow for September 17–19.

For tributary sites, the flow per unit area (the area of the drainage basin) was related to the location of the drainage network within the Laurel Hill Creek Basin. Tributaries with a drainage network that extends into the western sections of the basin and thus receives some recharge water from the western ridge had higher flows per unit area than tributaries with

Table 3. Measured streamflow and drainage area for surface-water sites sampled in the Laurel Hill Creek Basin, southwestern Pennsylvania, 2007.

[yyyymmdd, year, month, day; ft^3/s, cubic feet per second; DA, drainage area; mi^2, square miles; SF/A, streamflow per area; $ft^3/s/mi^2$, cubic feet per second per square mile; in/yr, inches per year]

Station number	Local identifier	Latitude (decimal degrees)	Longitude (decimal degrees)	Date, yyyym-mdd	Time	Stream-flow, ft^3/s	DA, mi^2	SF/A, $ft^3/s/mi^2$	SF/A, in/yr
				Tributaries					
03079350	Crab Run	40.0611	-79.1658	20070627	1330	0.2	4.12	0.05	0.66
03079400	Clear Run	40.0742	-79.1772	20070625	1115	1.5	4.98	0.30	4.09
03079400	Clear Run	40.0742	-79.1772	20070917	1110	1.5	4.98	0.30	4.09
03079418	Shanks Run	40.0589	-79.1914	20070627	1315	0.09	0.8	0.11	1.53
030794464	Moore Run	40.0681	-79.2092	20070627	1245	0.06	0.67	0.09	1.22
030794464	Moore Run	40.0681	-79.2092	20070919	1300	0.13	0.67	0.19	2.63
030794467	Shafer Run	40.0531	-79.2014	20070627	1230	1.2	4.89	0.25	3.33
030794467	Shafer Run	40.0531	-79.2014	20070917	1230	1.4	4.89	0.29	3.89
03079480	Kooser Run	40.0442	-79.2175	20070625	1215	2.4	3.76	0.64	8.66
03079480	Kooser Run	40.0442	-79.2175	20070917	1200	2.3	3.76	0.61	8.30
03079520	Gross Run	40.0319	-79.2250	20070627	1130	0.25	1.17	0.21	2.90
03079520	Gross Run	40.0319	-79.2250	20070919	1210	0.46	1.17	0.39	5.34
03079540	Crise Run	40.0281	-79.2286	20070627	1145	0.2	0.92	0.22	2.95
03079540	Crise Run	40.0281	-79.2286	20070919	1130	0.16	0.92	0.17	2.36
03079580	Buck Run	40.0189	-79.2411	20070627	1100	0.18	0.87	0.21	2.81
03079580	Buck Run	40.0189	-79.2411	20070919	1110	0.15	0.87	0.17	2.34
03079640	Jones Mill Run	40.0025	-79.2356	20070627	1030	2.4	4.92	0.49	6.62
03079640	Jones Mill Run	40.0025	-79.2356	20070918	1615	2.6	4.92	0.53	7.17
03079670	Allen Creek	39.9858	-79.2628	20070625	1500	1.9	4.6	0.41	5.61
03079670	Allen Creek	39.9858	-79.2628	20070917	1500	1.6	4.6	0.35	4.72
03079700	Garys Run	39.9736	-79.2992	20070627	945	0.12	1.22	0.10	1.34
03079700	Garys Run	39.9736	-79.2992	20070919	940	0.13	1.22	0.11	1.45
03079704	Cole Run	39.9728	-79.2839	20070919	1010	0.06	1.06	0.06	0.77
03079708	Blue Hole Creek	39.9589	-79.2853	20070627	930	0.75	5.83	0.13	1.75
03079708	Blue Hole Creek	39.9589	-79.2853	20070918	1530	0.88	5.83	0.15	2.05
03079710	Fall Creek	39.9579	-79.2798	20070625	1530	1.7	12.55	0.14	1.84
03079710	Fall Creek	39.9579	-79.2798	20070917	1615	1.6	12.55	0.13	1.73
03079740	Lost Creek	39.9475	-79.2658	20070625	1645	0.24	4.16	0.06	0.78
03079740	Lost Creek	39.9475	-79.2658	20070918	1445	0.24	4.16	0.06	0.78
03079770	Whipkey Run	39.9136	-79.3061	20070626	1330	0.07	2.54	0.03	0.37
03079770	Whipkey Run	39.9136	-79.3061	20070918	1200	0.07	2.54	0.03	0.37
03079786	Mose King Run	39.9008	-79.3108	20070626	1130	0.02	2.21	0.01	0.12
03079830	Sandy Run	39.9331	-79.3367	20070626	1415	0.73	5	0.15	1.98
03079830	Sandy Run	39.9331	-79.3367	20070918	1130	1	5	0.20	2.71
03079850	Harbaugh Run	39.9244	-79.3569	20070627	830	0.19	1.91	0.10	1.35

Table 3. Measured streamflow and drainage area for surface-water sites sampled in the Laurel Hill Creek Basin, southwestern Pennsylvania, 2007.—Continued

[yyyymmdd, year, month, day; ft^3/s, cubic feet per second; DA, drainage area; mi^2, square miles; SF/A, streamflow per area; $ft^3/s/mi^2$, cubic feet per second per square mile; in/yr, inches per year]

Station number	Local identifier	Latitude (decimal degrees)	Longitude (decimal degrees)	Date, yyyym-mdd	Time	Stream-flow, ft^3/s	DA, mi^2	SF/A, $ft^3/s/mi^2$	SF/A, in/yr
03079900	Cranberry Glade Run	39.9008	-79.3683	20070626	1545	0.18	2.68	0.07	0.91
03079900	Cranberry Glade Run	39.9008	-79.3683	20070918	1045	0.39	2.68	0.15	1.98
03079926	May Run	39.8761	-79.3203	20070627	740	0.01	0.35	0.03	0.39
03079939	Coke Oven Hollow	39.8614	-79.3181	20070627	650	0.08	1.65	0.05	0.66
03079939	Coke Oven Hollow	39.8614	-79.3181	20070919	830	0.19	1.65	0.12	1.56
03079967	Smith Hollow	39.8561	-79.3172	20070626	945	0.12	3.94	0.03	0.41
03079967	Smith Hollow	39.8561	-79.3172	20070918	945	0.22	3.94	0.06	0.76
03079990	Paddytown Hollow	39.8436	-79.3128	20070626	915	0.1	3.23	0.03	0.42
03079990	Paddytown Hollow	39.8436	-79.3128	20070919	800	0.19	3.23	0.06	0.80
Main stem									
03079320	Laurel Hill Creek (1st)	40.0361	-79.1781	20070625	930	0.1	4.36	0.02	0.31
03079320	Laurel Hill Creek (1st)	40.0361	-79.1781	20070919	1340	0.47	4.36	0.11	1.46
03079420	Laurel Hill Creek (A0-2)	40.0558	-79.1892	20070625	1030	3.5	20.6	0.17	2.31
03079420	Laurel Hill Creek (A0-2)	40.0558	-79.1892	20070917	1030	3.9	20.6	0.19	2.57
03079447	Laurel Hill Creek (A2)	40.0439	-79.2031	20070625	1145	2.8	26.3	0.11	1.45
03079447	Laurel Hill Creek (A2)	40.0439	-79.2031	20070917	945	2.7	26.3	0.10	1.39
03079550	Laurel Hill Creek (A3)	40.0256	-79.2222	20070625	1300	5.7	35.7	0.16	2.17
03079550	Laurel Hill Creek (A3)	40.0256	-79.2222	20070917	1300	5.8	35.7	0.16	2.21
03079600	Laurel Hill Creek (A4-1)	40.0089	-79.2344	20070625	1330	4.1	38.2	0.11	1.46
03079600	Laurel Hill Creek (A4-1)	40.0089	-79.2344	20070917	1400	7.2	38.2	0.19	2.56
03079660	Laurel Hill Creek (A4-2)	39.9861	-79.2586	20070625	1415	10	48.2	0.21	2.82
03079660	Laurel Hill Creek (A4-2)	39.9861	-79.2586	20070917	1430	10	48.2	0.21	2.82
03079714	Laurel Hill Creek (A5)	39.9522	-79.2703	20070625	1600	15	69.83	0.21	2.92
03079714	Laurel Hill Creek (A5)	39.9522	-79.2703	20070917	1540	14	69.83	0.20	2.72
03079744	Laurel Hill Creek (A5A)	39.9375	-79.2711	20070625	1700	11	75.6	0.15	1.98
03079744	Laurel Hill Creek (A5A)	39.9375	-79.2711	20070918	1350	14	75.6	0.19	2.51
03079748	Laurel Hill Creek (A6)	39.9200	-79.2800	20070626	1245	12	78.9	0.15	2.06
03079748	Laurel Hill Creek (A6)	39.9200	-79.2800	20070918	1315	12	78.9	0.15	2.06
03079942	Laurel Hill Creek (A8)	39.8589	-79.3206	20070626	1030	18	109	0.17	2.24
03079942	Laurel Hill Creek (A8)	39.8589	-79.3206	20070918	915	18	109	0.17	2.24
03079993	Laurel Hill Creek (A9)	39.8400	-79.3231	20070626	830	20	119	0.17	2.28
03079993	Laurel Hill Creek (A9)	39.8400	-79.3231	20070918	830	18	119	0.15	2.05
03080000	Laurel Hill Creek (U)	39.8204	-79.3214	20070626	730	16	121	0.13	1.79
03080000	Laurel Hill Creek (U)	39.8204	-79.3214	20070918	745	20	121	0.17	2.24

a drainage network that is primarily in the eastern or central parts of the basin. The mean flow per unit area for tributaries draining eastern or central sections was 0.05 cubic feet per second per square mile ($ft^3/s/mi^2$) or about 0.7 inches per year (in/yr). Tributaries draining areas that extend into the western ridge had a mean flow per unit area of 0.24 $ft^3/s/mi^2$ or about 3 in/yr (table 3). Areas along the western ridge of the basin have the highest annual precipitation rates due to orographic influences (fig. 4); in addition, ridge tops typically have higher recharge rates than adjacent areas as a result of the proximity of the bedrock to land surface, which promotes recharge to groundwater aquifers due to the typically shallow nature of soils along the ridges. Farther down in the basin, the soils are deeper; the water can be captured within the soil zone and then can be evaporated or transpired to a greater extent relative to ridge top locations. The tributaries with the highest mean flow per unit area were Kooser Run (0.62 $ft^3/s/mi^2$), Jones Mill Run (0.51 $ft^3/s/mi^2$), and Allen Creek (station 03079670; 0.38 $ft^3/s/mi^2$). The drainage areas for these three streams are all greater than 3.7 mi^2. The tributaries with the lowest flow per unit area were Mose King Run (station 03079786) (0.01 $ft^3/s/mi^2$), Whipkey Run (station 03079770; 0.03 $ft^3/s/mi^2$), and May Run (0.03 $ft^3/s/mi^2$). These three streams all drain areas in the central to eastern part of the basin, and they all have drainage areas less than 2.6 mi^2.

As indicated above, the amount of flow per unit area at the tributary sites was affected by the size of the drainage area. Tributary subbasins with a drainage area less than 3 mi^2 had a mean flow per unit area of 0.12 $ft^3/s/mi^2$, whereas tributary sites with a drainage area greater than 3 mi^2 had a mean flow per unit area of 0.23 $ft^3/s/mi^2$. One reason (in addition to effects of spatial location and subsequent topographic influences) for the difference between small and (relatively) large tributary subbasins is that groundwater beneath the smaller subbasins can flow more readily to an adjacent subbasin than groundwater beneath large subbasins.

The tributary sites with large drainage areas had higher flow per unit area than main-stem sites along Laurel Hill Creek. The average flow per unit area for the main stem sites was 0.16 $ft^3/s/mi^2$. The main stem of the creek integrates the recharge water from both sides of the basin, so it is reasonable to think that the main stem could have lower flow per unit area than tributary sites draining the western ridge. There are major water withdrawals in the basin from the surface-water and groundwater systems. On the basis of 2009 water-use data, 1.04 Mgal/d (1.61 ft^3/s) was removed directly from the surface-water system (table 4), all from the main stem in the upper part of the basin. The groundwater withdrawals occurred across the basin but were primarily concentrated along the western ridge in the northern one-half of the basin. The effects of water withdrawals on streamflow would be most apparent for the main stem because drainage area for the main stem integrates all water withdrawals. The daily net withdrawal rate from surface water and groundwater of 1.93 Mgal/d is equal to 3.0 ft^3/s. If this net withdrawal is added to the measured flows for all the sites along the main stem downstream from the drinking water reservoir in Bakersville [the reservoir is immediately upstream from surface-water site LHC-A2 (station 03079447); fig. 8], the mean flow per unit area for the main stem sites is 0.22 $ft^3/s/mi^2$, which is slightly less than the flow per unit area for larger tributary sites.

Streamflow measured along the main stem of Laurel Hill Creek showed a fairly stable flow to unit area relation in the middle to lower sections of the basin, whereas the upper section was affected by drainage-area size and water withdrawals. The upper most site sampled along the main stem (LHC-1st) had a mean flow per unit area of 0.07 $ft^3/s/mi^2$, which was the lowest ratio for all sites sampled on the main stem. Site LHC-A0-2 (station 03079420) upstream from the drinking-water reservoir in Bakersville had a mean value of 0.18 $ft^3/s/mi^2$, but the value was substantially less for LHC-A2 (mean, 0.10 $ft^3/s/mi^2$), which is downstream from the drinking-water reservoir. Downstream from the drinking-water reservoir, nine measurements were made at main-stem sites during both synoptic events, and the mean values ranged from 0.15 to 0.21 $ft^3/s/mi^2$. The highest values were for two sites [LHC-A4-2 (station 03079660) and LHC-A5 (station 03079714)] immediately downstream from Laurel Hill Lake (table 3). It appears that the lake was augmenting flow during low-flow periods.

Water Use

According to water-use data compiled for 2003 and 2009, the net water withdrawals from the basin (both groundwater and surface-water sources) equaled 2.01 and 1.93 Mgal/d, respectively. Data for 2009 indicate that the total withdrawals equaled 2.22 Mgal/d, whereas the total discharges equaled 0.29 Mgal/d (table 4). For registered users, 1.04 and 0.95 Mgal/d were from surface-water and groundwater sources, respectively, with the remaining 0.23 Mgal/d attributed to non-registered users. Approximately 57 percent of the registered withdrawals were attributed to public-water suppliers. It is likely that most of the unregistered withdrawals were from either groundwater wells or springs. Approximately 39 and 43 percent of the unregistered withdrawals were attributed to commercial entities and agriculture, respectively; the remaining unregistered use was primarily residential.

There were only six registered discharge locations in the basin. Sixty-five percent of the discharge water came from the dewatering of a quarry; this water was discharged back into the surface-water system. Twenty percent of the total discharge water was wastewater, and the remaining 15 percent was back flow from the water-treatment plant of a public-water supplier. One public-water supplier in the basin exports wastewater to an adjacent basin. The average daily export of wastewater using data from 2005 to 2010 was 1.10 Mgal/d (1.71 ft^3/s).

During times of drought, total water use in the basin theoretically drops by 0.04 Mgal/d, based on reduced withdrawals by one of the public-water suppliers in the basin. The drought contingency plan (in place during the late 2000s) developed

Table 4. Summary of water discharges and withdrawals within Laurel Hill Creek Basin, southwestern, Pennsylvania, 2009.

[> =, greater than or equal to; --, no data; Mgal/d, million gallons per day]

Water use	Number of water use points	Number of values > = 0.01 Mgal/d	Water use, in Mgal/d				Percent of total water use
			Mean	Minimum	Maximum	Total	
Discharges							
All discharges	6	3	0.05	0.00	0.19	0.29	--
Withdrawals							
All withdrawals	377	12	--	--	--	2.22	--
Summary of withdrawals by source							
Groundwater[1]	17	8	0.06	0.00	0.21	0.95	43
Surface water[1]	2	2	0.52	0.18	0.86	1.04	47
Unidentified[2]	358	2	0.00	0.00	0.08	0.23	10
Summary of withdrawals by water-use category							
Registered							
Water supplier	6	6	0.21	0.01	0.86	1.27	57
Commercial	10	3	0.05	0.00	0.18	0.49	22
Mineral	3	1	0.08	0.00	0.21	0.23	10
Estimated unregistered							
Residential	277	0	0.00	0.00	0.00	0.03	1
Industrial	5	0	0.00	0.00	0.00	0.01	1
Commercial	52	1	0.00	0.00	0.08	0.09	4
Agriculture (Livestock)	24	1	0.00	0.00	0.02	0.10	4

[1]Described in registration data; does not include estimated water use.

[2]Estimated water use not identitifed as groundwater or surface water.

by the Somerset Borough Water Authority calls for substantial reductions in surface-water withdrawals but also substantial increases in groundwater withdrawals (Lawrence Kowatch, Somerset Borough Water Authority, written commun., 2010). The net effect is a 0.04 Mgal/d decrease. Surface water is withdrawn in the upper part of the Laurel Hill Creek Basin, and according to PaDEP, the primary water supplier must allow 1.37 Mgal/d to pass through the primary reservoir used for the intake of surface water. Once flow through the reservoir drops below 1.37 Mgal/d, surface-water withdrawals are terminated and almost all of the water withdrawn in the basin is taken from groundwater sources.

Water-Analysis Screening Tool (WAST)

The WAST calculates a safe yield for different pour points within the basin (Stuckey, 2008). Water withdrawals in the Laurel Hill Creek Basin are primarily in the upper part of the basin. The total drainage area of the basin at the mouth equals 125 mi^2. Approximately 80 percent of the water withdrawals occur within the upper 36 mi^2 of the basin. One aspect of the WAST to note is that the value of a withdrawal from a groundwater well is equal to the value of a withdrawal from a surface-water site. This is based on the premise that one gallon of water removed from a well is one gallon of water that would not reach the receiving stream body. Given this algorithm within the WAST, the safe yield in the upper part of the basin at LHC-A3 (station 03079550; drainage area, 35.7 mi^2) (ISC or safe yield equals 0.315 Mgal/d) is exceeded by the net withdrawals (1.490 Mgal/d) by 372 percent. Just upstream, at LHC-A2 (station 03079447; drainage area, 26.3 mi^2), the ISC (0.215 Mgal/d) is exceeded by the net withdrawals (1.101 Mgal/d) by about 412 percent (table 5). In between these locations, there are two public-supply wells in the Shafer Run subbasin. The primary water-withdrawal sites in the basin are just upstream from LHC-A2, which is just downstream from a surface-water reservoir with the primary surface-water intake in the basin.

According to criteria established by PaDEP in the context of Act 220 (the Pennsylvania State Water Plan), a safe amount of water to withdraw on a daily basis from the entire Laurel Hill Creek Basin is 1.43 Mgal/d. The safe amount of water to withdraw in Mgal/d is equal to the ISC (table 5). Using 2009 water-use data, the total withdrawal was 2.22 Mgal/d, and the total discharge was 0.29 Mgal/d. The total discharge value used by the WAST for the 2009 data was 0.33 Mgal/d, which includes a conservation release value of 0.035 Mgal/d for a pond in the central part of the basin. The net withdrawals exceed the safe yield (ISC) for the basin by about 0.46 Mgal/d (about 32 percent) at the mouth of the basin (table 5). The ISC less net withdrawals is equal to the Screening Indicator (SI) in Mgal/d. The exceedance of the safe yield by the net withdrawals in the basin was the primary reason that the Laurel Hill Creek Basin was nominated as a Critical Water Planning Area in 2010 by PaDEP.

Three subbasins had more than 0.1 Mgal/d of net withdrawals during 2009. These withdrawals were primarily from groundwater wells, but there were some withdrawals from spring sources. The subbasin most affected by water withdrawals is Allen Creek (drainage area, 4.6 mi^2), where withdrawals were approximately 0.36 Mgal/d, which equates to about a 1,280 percent exceedance of a safe yield for the basin (table 5). The Kooser Run subbasin had net withdrawals of 0.31 Mgal/d for 2009, which exceeded the safe yield for this 4.6 mi^2 subbasin by 1,060 percent. The primary water user in this subbasin is a limestone quarry in the upper part of the subbasin. Another subbasin that has significant water withdrawals is Shafer Run (drainage area, 4.89 mi^2), where the safe yield is exceeded by 566 percent (table 5). In this subbasin, reduction in habitat loss in the stream channel has been documented by the Pennsylvania Fish and Boat Commission. The Commission observed streamflow to be intermittent in the channel that historically has been perennial, and this intermittent streamflow has substantially reduced the game (trout) fish community in the stream (Mike Depew, Pennsylvania Fish and Boat Commission, written commun., 2010). Even though the

Table 5. Summary of water withdrawals, discharges, and screening indicators from the Water Analysis Screening Tool (WAST) for stream sites in the Laurel Hill Creek Basin, southwestern, Pennsylvania, 2009.

[mi^2, square miles; ISC, initial screening criteria; Mgal/d, million gallons per day; SI, screening indicator; %, percent]

Stream name	Latitude (decimal degrees)	Longitude (decimal degrees)	Drainage area (mi^2)	ISC (Mgal/d)	Total withdrawals (Mgal/d)	Total discharges (Mgal/d)	SI (Mgal/d)	SI (%)
Tributaries								
Crab Run	40.0610	-79.1728	4.17	0.022	0.0136	0.000	0.008	37.26
Clear Run	40.0653	-79.1728	5.43	0.033	0.0037	0.000	0.029	88.57
Shafer Run	40.0507	-79.2000	4.93	0.028	0.1895	0.000	-0.161	-566.18
Kooser Run	40.0378	-79.2107	4.62	0.027	0.5347	0.227	-0.281	-1059.87
Jones Mill Run	40.0020	-79.2348	4.96	0.029	0.0189	0.000	0.010	34.77
Spruce Run	39.9879	-79.2403	2.41	0.011	0.0058	0.000	0.005	47.54
Allen Creek	39.9850	-79.2608	4.60	0.026	0.3599	0.000	-0.334	-1279.56
Blue Hole Creek	39.9592	-79.2856	5.82	0.035	0.0042	0.000	0.031	88.00
Fall Creek	39.9588	-79.2790	12.55	0.089	0.0051	0.000	0.084	94.26
Lost Creek	39.9479	-79.2654	4.15	0.021	0.0084	0.004	0.016	78.33
Whipkey Run	39.9125	-79.3057	2.55	0.011	0.0007	0.000	0.011	94.12
Sandy Run	39.8982	-79.3235	10.76	0.073	0.0051	0.000	0.068	93.04
Harbaugh Run	39.9184	-79.3387	2.68	0.013	0.0003	0.000	0.013	97.57

Table 5. Summary of water withdrawals, discharges, and screening indicators from the Water Analysis Screening Tool (WAST) for stream sites in the Laurel Hill Creek Basin, southwestern, Pennsylvania, 2009.—Continued

[mi^2, square miles; ISC, initial screening criteria; Mgal/d, million gallons per day; SI, screening indicator; %, percent]

Stream name	Latitude (decimal degrees)	Longitude (decimal degrees)	Drainage area (mi^2)	ISC (Mgal/d)	Total withdrawals (Mgal/d)	Total discharges (Mgal/d)	SI (Mgal/d)	SI (%)
Cranberry Glade Run	39.8828	-79.3261	5.16	0.029	0.0027	0.000	0.027	90.67
Smith Hollow	39.8565	-79.3167	3.94	0.019	0.0018	0.000	0.017	90.39
Paddytown Hollow	39.8437	-79.3128	3.23	0.015	0.0006	0.000	0.014	96.07
Main stem								
Laurel Hill Creek (1st)	40.0361	-79.1781	4.33	0.022	0.0269	0.000	-0.005	-20.37
Laurel Hill Creek (A0-1)	40.0532	-79.1660	8.70	0.053	0.0284	0.000	0.024	46.12
Laurel Hill Creek (A0-2)	40.0558	-79.1892	20.58	0.157	0.0513	0.000	0.106	67.40
Laurel Hill Creek (A2)	40.0439	-79.2031	26.34	0.215	1.1012	0.000	-0.886	-411.88
Laurel Hill Creek (A3)	40.0256	-79.2222	35.69	0.315	1.7638	0.274	-1.174	-372.42
Laurel Hill Creek (A4-1)	40.0089	-79.2344	38.15	0.342	1.7652	0.274	-1.149	-336.09
Laurel Hill Creek (A4-2)	39.9861	-79.2586	48.22	0.457	1.7907	0.324	-1.009	-220.95
Laurel Hill Creek (A5)	39.9522	-79.2703	69.83	0.724	2.1606	0.324	-1.112	-153.45
Laurel Hill Creek (A5A)	39.9375	-79.2711	75.40	0.792	2.1697	0.328	-1.050	-132.59
Laurel Hill Creek (A6-1)	39.9200	-79.2800	78.77	0.833	2.1744	0.328	-1.013	-121.64
Laurel Hill Creek (A7)	39.8817	-79.3253	98.46	1.092	2.1873	0.328	-0.767	-70.30
Laurel Hill Creek (A8)	39.8589	-79.3206	109.89	1.243	2.1989	0.328	-0.628	-50.52
Laurel Hill Creek (A9)	39.8400	-79.3231	118.73	1.359	2.1824	0.258	-0.566	-41.67
Laurel Hill Creek (U)	39.8204	-79.3214	121.04	1.387	2.2120	0.328	-0.496	-35.77
Laurel Hill Creek (mouth)	39.8146	-79.3613	124.65	1.432	2.2154	0.328	-0.455	-31.76

WAST was developed for drainage areas of 15 mi^2 or greater, results for these subbasins indicate that water use is relatively high for the size of the subbasins, and, in at least one instance (Shafer Run), the streamflow has been visually depleted beyond typical conditions observed in the past.

Simulation of Surface-Water and Groundwater Flow

A GSFLOW model was developed for the basin as a tool to determine the manner in which future changes in water use and land use could affect the water availability for human consumption and aquatic resources. The calibration of the coupled GSFLOW model necessitated some parameter modification of the uncoupled calibrated models that were developed in PRMS and MODFLOW. The groundwater flow components of PRMS were replaced by MODFLOW processes in the coupled model. The movement of water from surface processes (as defined by PRMS) through the unsaturated zone to MODFLOW finite-difference cells also affected the water balance for the MODFLOW portion; therefore, parameter adjustments in PRMS and MODFLOW were necessary once the models were coupled in GSFLOW.

Surface Runoff–PRMS Model

The PRMS model requires an input parameter file that defines the movement of water through the delineated basin. The basin parameterization controls the amount of water lost through evapotranspiration (ET), the amount of water stored in the snowpack (during winter), soil zone, canopy, and land surface, and the amount of water that runs off directly to streams. Water that is not lost to ET or direct runoff, and is not stored in the upper soils zone and land surface, is recharged to the groundwater and subsurface reservoirs where it flows out slowly to the stream. The input to PRMS consists of daily air temperature (maximum and minimum) and daily precipitation.

Climate Data

Eleven weather stations were used to develop the input maximum and minimum daily air temperatures and daily precipitation to PRMS (table 6). The eleven stations were accessed from the cooperative weather station network maintained by the National Climatic Data Center (2008) of the National Oceanic and Atmospheric Administration (http://www.ncdc.noaa.gov/cdo-web/search). No stations were located within the basin boundaries, so the best available network of nearby stations was used. The closest station to the basin is in Confluence, Pa., just 1 mi from the southern boundary; the farthest station is in New Stanton, Pa., 21 mi from the northwestern basin boundary. Station elevations range from 950 to 2,100 ft above NAVD 88. Precipitation data were available for all 11 stations for the model period of January 1, 1991, through September 29, 2007. Two of the stations did not have maximum and minimum temperature data for this period. Some stations were missing daily values for the three climatic variables. Estimates for these missing values were necessary to avoid computational errors in model output. Values for the stations with data for a particular day were used to fill in missing gaps.

Solar-radiation data were available for three weather stations at airports (table 7). Data were supplied by the Northeast Regional Climate Center (Keith Eggleston, Northeast Regional Climate Center, written commun., 2008) in units of langleys. The closest location to the basin boundary was the Johnstown airport (23 mi), and the farthest was the Pittsburgh airport (60 mi). Solar radiation data collected on a continuous daily basis were needed because any missing days would cause problems with modeled evapotranspiration for the basin.

Table 6. Description of climate stations used for input to the Laurel Hill Creek Basin, southwestern, Pennsylvania, GSFLOW model.

[NAVD 88, North American Vertical Datum of 1988; shading indicates no temperature data available]

Weather station number	Station name	Latitude	Longitude	Elevation, feet above NAVD 1988
361350	Chalk Hill	39°51'00"	79°34'48"	1,980
361705	Confluence	39°48'00"	79°22'12"	1,490
361726	Connellsville	40°00'00"	79°36'00"	900
362108	Derry	40°18'00"	79°19'48"	1,060
362183	Donegal	40°07'48"	79°24'00"	1,799
365686	Meyersdale	39°46'48"	79°02'24"	2,000
366042	Mount Pleasant	40°13'12"	79°30'00"	1,003
366310	New Stanton	40°12'00"	79°37'48"	950
367338	Rector	40°10'12"	79°16'12"	1,330
368244	Somerset	40°00'00"	79°04'48"	2,100
369050	Uniontown	39°54'36"	79°43'12"	956

Table 7. Description of solar-radiation stations used for input to the Laurel Hill Creek Basin, southwestern, Pennsylvania, GSFLOW model.

[Latitude and longitude are in degrees, minutes, and seconds]

Airport	Latitude	Longitude
Pittsburgh, PA	40°29'46"	80°15'24"
Morgantown, WV	39°38'34"	79°54'59"
Johnstown, PA	40°19'11"	78°50'01"

Hydrologic Response Units

The basin was divided into 718 HRUs (fig. 20) with a mean size of 111 acres. Most of the HRU boundaries were defined primarily by the stream network. Wherever a stream reach intersected another stream reach, a new HRU is defined. Either side of a stream channel is defined as an HRU (hence the two-dimensional approach as defined previously). The density of the drainage network in the Laurel Hill Creek Basin necessitated a large number of HRUs. HRUs in each drainage subbasin that are up-gradient from the perennial stream network were delineated on the basis of land use or slope.

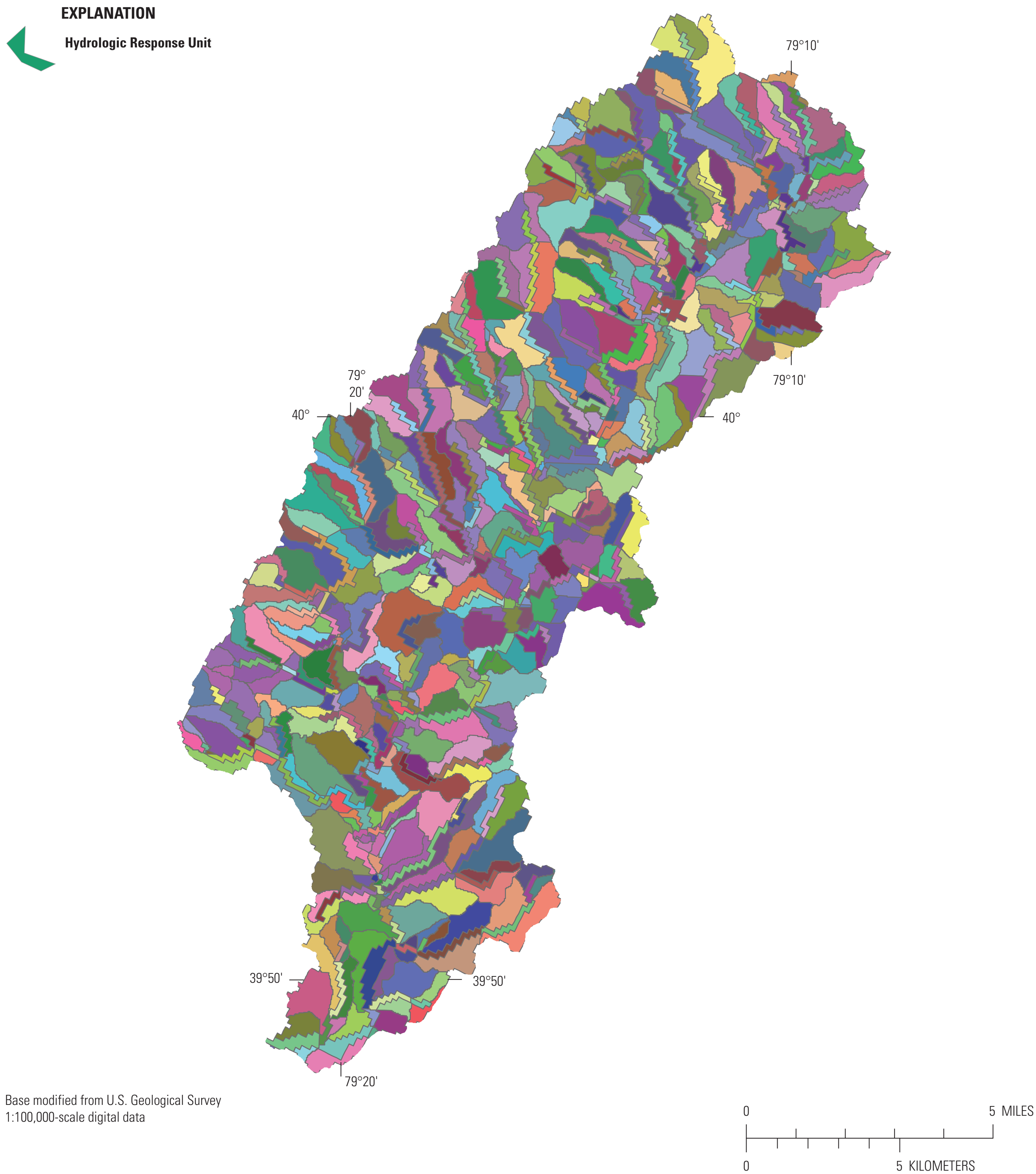


Figure 20. Hydrologic Response Units (HRU) in the Laurel Hill Creek Basin, southwestern, Pennsylvania, generated for the GSFLOW model.

PRMS Modules

Eleven different modules were used for the PRMS model prior to integration with MODFLOW in GSFLOW (table 8) for the Laurel Hill Creek Basin. Each module requires specific parameters defined by that particular module. Many parameters are used by more than one PRMS module (table 9 back of report). The number of values for each parameter is dependent on the dimensions for that particular parameter. A dimension defines the number of spatial features or stations or time series values. Physical characteristics of HRUs such as HRU area have the same number of values as the number of HRUs; therefore, variable "hru_area" has a dimension equal to the number of HRUs (nhru). Many climatic variables have a dimension equal to the number of months in the year (nmonths). Other parameters that are constant for the entire basin have a dimension equal to one (table 10).

Climatic PRMS Modules

Six different modules defined climatic variables for the PRMS and subsequently the GSFLOW model for this basin. Two modules (*ddsolrad_hru* and *soltab_hru*) control the distribution of solar radiation to each HRU (table 8). Module *ddsolrad_hru* adjusts solar radiation values on a monthly basis by using a relation between maximum air temperature and degree days. These monthly adjustments are then taken by the *soltab_hru* module to distribute potential solar radiation to each HRU (Markstrom and others, 2008).

Precipitation and temperature data were distributed to each HRU using a similar method. Modules *precip_dist2* and *temp_dist2* use a lapse rate computed from the number of available stations that is weighted by the inverse of the squared distance between each station and the centroid of each HRU (Markstrom and others, 2008) (table 8). Module *temp_dist2* uses elevation to adjust HRU temperatures, whereas the *precip_dist2* module uses only location relative to precipitation stations to adjust precipitation amounts to HRUs.

The accumulation and melting of snow for each HRU is controlled by the parameterization of variables included within the *snowcomp* module. Snow depletion curves were separately developed for HRUs with a predominant north or south aspect, and for HRUs classified by elevation. Using the mean elevation of an HRU, elevations were classified as being either above or below 2,350 ft above NAVD 88. The guide for the depletion curve development was Anderson (1973). Actual values used in the model and acceptable ranges for the different parameters are presented in table 11.

The *potet_jh* module defines evapotranspiration (ET) processes in the basin. This module uses the Jensen-Haise formulation to calculate potential evapotranspiration (Jensen and others, 1969). Air-temperature coefficients are used in the formulation to estimate potential ET (PET). Coefficients were developed on a monthly basis (parameter jh_coef; table 11) and for each HRU (parameter jh_coef_hru). HRU coefficients were generated primarily using elevation. Shevenell (1996) provides PET equations for each month that are functions of elevation; that work was used as an initial starting point to estimate coefficients for the Jensen-Haise formulation. The daily solar radiation data available from the input parameter file are also used in the equation to estimate PET. The precipitation generated by the *precip_dist2* module for the entire model period was 45.6 inches per year. The simulated flow for Laurel Hill Creek at Ursina was about 30 inches per year. Assuming almost a zero change in storage terms within the basin for the entire period, the difference between precipitation inputs and flow should approximate ET losses. Therefore, the coefficients used in the model (see table 11 for actual values) were adjusted along with other parameters that affect simulated ET values to derive annual rates of ET required to balance the water budget—about 15.6 inches. Parameters in the model that affect the simulated amount of water held in the upper soil layers also had a major effect on simulated ET values.

Basin-Characterization PRMS Modules

The *basin* module defines the total basin area and has pertinent details for each of the 718 HRUs for the Laurel Hill Creek Basin. This module defines the HRU area, slope, elevation, percent impervious surface, and the type of HRU (land or water) (table 8). The percent impervious surface was generated from an enhanced version of the USGS land cover GIS data (U.S. Geological Survey, 2004).

The *intcp* module defines the summer and winter cover density and cover type for each of the HRUs. These parameters are based on the USGS land cover data (2004). The cover type for the model is defined as grasses, shrubs, or trees. It is apparent from figure 3 that the predominant land cover for the Laurel Hill Creek Basin is forest. The cover density for winter and summer has a tremendous effect on ET processes and runoff characteristics. Winter cover greatly affects snowpack accumulation and duration. Mean cover density for summer (covden_sum) and winter (covden_win) was determined through GIS processes to equal 0.84 and 0.37, respectively (table 11).

The *soilzone* module is a critical aspect of the PRMS model due to the sensitivity of the model to parameters included within this module. Adjustments to specific parameters in this module greatly affect the simulated hydrologic response to precipitation events. The slope of the rise and recession of the hydrograph, along with the recession duration, are affected by numerous parameters defined in this module. The rate and movement of fast and slow interflow from the time water infiltrates the soil until it reaches the stream channel is solely dependent on parameters included within this module. Fast (fastcoef_lin and fastcoef_sq) and slow (slowcoef_lin and slowcoef_sq) interflow terms are defined in this module. Linear (_lin) and non linear (_sq) coefficients are available for both fast and slow movement; however, in the Laurel Hill Creek Basin, the _sq terms were set equal to zero for fast and slow interflow (table 11) to

Table 8. Description of modules used in the GSFLOW model for the Laurel Hill Creek Basin, southwestern, Pennsylvania.

[HRU, Hydrologic Response Unit; shading indicates a GSFLOW module; modules that are not shaded are PRMS modules that were used for the coupled model]

Module	Description
basin	Computes shared watershed-wide variables. Shared variables include the area of each HRU that is pervious and impervious determined on the basis of the fraction in each HRU that is impervious, the total area of the watershed determined as the sum of the area in each HRU.
cascade	Determines the computational order of the HRUs and groundwater reservoirs for routing flow downslope in a cascading pattern.
ddsolrad_hru	Distributes solar radiation to each HRU.
gsflow_budget	Calculates a watershed budget for GSFLOW and adjusts the final storage in gravity reservoirs using flows to and from finite-difference cells at the end of each time step.
gsflow_mf2prms	Used to integrate the spatial units and transfer dependent variables (model states and fluxes) and volumetric flow rates between PRMS and MODFLOW. Distributes groundwater discharge from finite-difference cells in MODFLOW to gravity reservoirs in the soil zone of PRMS.
gsflow_prms2mf	Used to integrate the spatial units and transfer dependent variables (model states and fluxes) and volumetric flow rates between PRMS and MODFLOW. Distributes gravity drainage from gravity reservoirs in the soil zone of PRMS to finite-difference cells in MODFLOW. The module also distributes surface runoff and interflow from HRUs to stream segments in MODFLOW.
gsflow_setconv	Determines a set of variables that are used in other GSFLOW modules to convert units between PRMS and MODFLOW during a simulation.
gsflow_sum	Calculates summary tables of the water balance at the end of each time step.
intcp	Calculates the amount of rain and snow that is intercepted by vegetation, the amount of evaporation of intercepted rain and snow, and the amount of net rain and snow throughfall that reaches the soil or snowpack.
potet_jh	Calculates the amount of potential evapotranspiration and determines if a time step is one of active transpiration in an HRU. Uses the Jensen-Haise formulation (Jensen and others, 1969) to calculate potential evapotranspiration.
precip_dist2	Distributes precipitation to each HRU and determines the form of precipitation (rain, snow, or a mixture of both). Distributes precipitation to HRUs using a lapse rate computed from two or more stations weighted by the inverse of the square of the distance between the centroid of an HRU and each station location.
snowcomp	Initiates development of a snowpack and simulates snow accumulation and depletion processes using an energy-budget approach.
soilzone	Calculates inflows to and outflows from the soil zone of each HRU and includes inflows from infiltration, groundwater, and upslope HRUs, and outflows to gravity drainage, interflow, and surface runoff to downslope HRUs.
soltab_hru	Calculates tables of 366 values of potential solar radiation and hours of sunlight for each HRU on the basis of representative slope, aspect, and latitude of each HRU. The module also computes a table of the potential solar radiation at the watershed centroid with a horizontal slope.
srunoff_smidx_casc	Used to compute surface runoff and infiltration for each HRU. Uses antecedent soil moisture and a non-linear variable-source-area method.
temp_dist2	Distributes maximum and minimum temperatures to each HRU using a lapse rate computed from two or more stations weighted by the inverse of the square of the distance between the centroid of an HRU and each station location.

Table 10. Description of dimension parameters used in the GSFLOW model for the Laurel Hill Creek Basin, southwestern, Pennsylvania.

[HRU, Hydrologic Response Unit]

Dimension	Number of values	Description
ncascade	1,469	Number of cascade paths associated with HRUs.
ncascdgw	1,469	Number of cascade paths associated with PRMS groundwater reservoirs.
ndays	366	Maximum number of days in a year.
ndepl	4	Number of snow-depletion curves used for snowmelt calculations.
ndeplval	44	Number of snow-depletion values for each snow-depletion curve.
ngw	718	Number of PRMS groundwater reservoirs. (used in PRMS-only simulations)
ngwcell	22,936	Number of MODFLOW finite-difference cells in a layer. (includes active and inactive cells)
nhru	718	Number of HRUs.
nhrucell	25,380	Number of unique intersections between gravity reservoirs in PRMS soil zone and MODFLOW finite difference cells.
nmonths	12	Number of months in a year.
nobs	1	Number of streamflow-gaging stations.
nrain	11	Number of measurement stations that measure precipitation.
nreach	2,423	Number of stream reaches on all stream segments.
nsegment	243	Number of stream segments.
nsol	3	Number of measurement stations that measure solar radiation.
nssr	718	Number of PRMS subsurface reservoirs. (must be specified equal to nhru)
ntemp	9	Number of measurement stations that measure air temperature.
one	1	A constant.

simplify the solution as other modelers have done (David Bjerklie, USGS, written commun., 2009). These parameters not only affect the stormflow peaks and shape of a storm hydrograph, but also affect the amount of water available for base flow after storm events. Other parameters in this module have a substantial effect on the simulated hydrograph, including "soil2gw_max," "pref_flow_den," and "ssr2gw_rate." Parameter "soil2gw_max" is the maximum value of soil-water excess routed directly to PRMS groundwater reservoirs. For this model, "soil2gw_max" was set very close to zero (mean for all HRUs was equal to about 0.04 in.; table 11) so that most water during storm events was routed to subsurface recharge (interflow) but not to groundwater reservoirs in PRMS (or MODFLOW finite-difference cells in the coupled model). A decrease in the values for this parameter reduces groundwater flow and increases subsurface flow and surface runoff. Parameter "pref_flow_den" is the decimal fraction of the soil zone available for preferential flow. A decrease in this parameter causes an increase in ET because more water is available in the upper part of the soil zone to be lost through ET processes. A change in "pref_flow_den" affects the partitioning of subsurface flow into fast and slow components.

Table 11. Summary of GSFLOW model parameters for Laurel Hill Creek Basin, southwestern, Pennsylvania, including dimensions, number of values specified, units, minimum, maximum, mean, the acceptable range, and default values for each parameter.

[If dimension was equal to one, the mean value is the one value used in the Laurel Hill Creek watershed model; dec. frac., decimal fraction; cal, calories; °C, degrees Celsius; >, greater than; °F, degrees Fahrenheit; gm, grams; cm^3, cubic centimeter]

Parameter	Dimension	Number of values	Units	Minimum	Maximum	Mean	Range	Default
adjmix_rain	nmonths	12	dec. frac.	0.48	1	0.80	0 – 3	1
albset_rna	one	1	dec. frac.			0.8	0 – 1	0.8
albset_rnm	one	1	dec. frac.			0.6	0 – 1	0.6
albset_sna	one	1	inches			0.05	0.001 – 1	0.05
albset_snm	one	1	inches			0.2	0.001 – 1	0.2
basin_area	one	1	acres			79,571.1	0 – $1X10^9$	0
basin_solsta	one	1	none			2	0 – 3	0
basin_tsta	one	1	none			2	0 – 9	1
carea_max	nhru	718	dec. frac.	0.054	0.246	0.090	0 – 1	0.6
cascade_flg	one	1	none			0	0 – 1	0
cascade_tol	one	1	acres			1	0 – 99	5
cecn_coef	nmonths	12	cal per °C > 0	12	12	12	0 – 20	5
circle_switch	one	1	none			1	0 – 1	1
cov_type	nhru	718	none	1	3	2.7	0 – 3	3
covden_sum	nhru	718	dec. frac.	0.15	1	0.84	0 – 1	0.5
covden_win	nhru	718	dec. frac.	0.08	0.84	0.37	0 – 1	0.5
dday_intcp	nmonths	12	degree days	-10	-10	-10	-60 – 4	-10
dday_slope	nmonths	12	degree days / °F	0.4	0.4	0.4	0.2 – 0.7	0.4
den_init	one	1	gm/cm^3			0.15	0.01 – 0.5	0.1
den_max	one	1	gm/cm^3			0.6	0.1 – 0.8	0.6
dist_max	one	1	gm/cm^3			1,056,000	1– $1X10^{10}$	$1X10^{10}$
elev_units	one	1	none			0	0 – 1	0
emis_noppt	one	1	dec. frac.			0.75	0.757 – 1	0.757
epan_coef	nmonths	12	none	1	1	1	0.2 – 3	1
fastcoef_lin	nhru	718	1/day	0.024	0.190	0.108	0 – 1	0.1
fastcoef_sq	nhru	718	none	0	0	0	0 – 1	0.8
freeh2o_cap	one	1	dec. frac.			0.01	0.01 – 0.2	0.05
gvr_cell_id	nhrucell	25,380	none	36	22,906		0 – 22936	1
gvr_cell_pct	nhrucell	25,380	dec. frac.	0			0 – 1	0
gvr_hru_id	nhrucell	25,380	none		1.000	0.562	0 – 718	1
gvr_hru_pct	nhrucell	25,380	dec. frac.	0	1.000	0.028	0 – 1	0
hru_area	nhru	718	acres	1.23	580.92	110.82	0.0–$1X10^{10}$	1
hru_aspect	nhru	718	degrees	47.06	311.94	168.70	0 – 360	0
hru_deplcrv	nhru	718	none	1	4	3.6	0 – 4	1
hru_down_id	ncascade	1,469	none	0	715		0 – 718	0
hru_elev	nhru	718	feet	1,324	2,915	2,136	-1,000 – 30,000	0
hru_lat	nhru	718	degrees	39.810	40.112	39.973	-90 – 90	40
hru_pct_up	ncascade	1,469	dec. frac.	0	1	0.49	0 – 1	1
hru_percent_imperv	nhru	718	dec. frac.	0	0.686	0.005	0 – 0.999	0
hru_slope	nhru	718	dec. frac.	0.007	0.418	0.141	0 – 10	0

Table 11. Summary of GSFLOW model parameters for Laurel Hill Creek Basin, southwestern, Pennsylvania, including dimensions, number of values specified, units, minimum, maximum, mean, the acceptable range, and default values for each parameter.—Continued

[If dimension was equal to one, the mean value is the one value used in the Laurel Hill Creek watershed model; dec. frac., decimal fraction; cal, calories; °C, degrees Celsius; >, greater than; °F, degrees Fahrenheit; gm, grams; cm^3, cubic centimeter]

Parameter	Dimension	Number of values	Units	Minimum	Maximum	Mean	Range	Default
hru_solsta	nhru	718	none	2	2	2	0 – 3	0
hru_strmseg_down_id	ncascade	1,469	none	0	243		0 – 243	0
hru_type	nhru	718	none	1	1	1	0 – 3	1
hru_up_id	ncascade	1,469	none	1	718		0 – 718	1
hru_xlong	nhru	718	feet	1,507,759.44	1,578,979.83	1,542,182.94	(- to +) $1X10^{10}$	0
hru_ylat	nhru	718	feet	177,801.17	287,060.83	236,645.31	(- to +) $1X10^{10}$	0
id_obsrunoff	one	1	none			1	0 – 1	0
imperv_stor_max	nhru	718	inches	0.001	0.001	0.001	0 – 10	0
jh_coef	nmonths	12	1/ °F	0	0.008	0.004	0.005 – 0.06	0.014
jh_coef_hru	nhru	718	°F	21.205	23.013	22.090	5 – 20	13
lapsemax_max	nmonths	12	°F	-3	3	-0.86	-3 – 3	2
lapsemax_min	nmonths	12	°F	-7	-6	-6.47	-7 – -3	-6.5
lapsemin_max	nmonths	12	°F	2.5	3.5	3.02	-2 – 4	3
lapsemin_min	nmonths	12	°F	-5	-3	-3.99	-7 – -3	-4
max_psta	one	1	none			11	2 – 50	50
max_tsta	one	1	none			9	2 – 50	50
maxday_prec	one	1	inches			12	0 – 20	15
melt_force	one	1	Julian day			10	1 – 366	90
melt_look	one	1	Julian day			1	1 – 366	90
mnsziter	one	1	none			22	1 – 200	4
monmax	nmonths	12	°F	73	102	88	0 – 115	100
monmin	nmonths	12	°F	-22	40	10	-60 – 65	-60
mxsziter	one	1	none			50	2 – 200	15
potet_sublim	one	1	dec. frac.			0.1	0.1 – 0.75	0.5
ppt_rad_adj	nmonths	12	inches	0.02	0.02	0.02	0 – 0.5	0.02
precip_units	one	1	none			0	0 – 1	0
pref_flow_den	nhru	718	dec. frac.	0.033	0.111	0.072	0 – 1	0
psta_mon	nrain X nmonths	132	inches	2.27	5.51	3.70	0.00001 – 50	1
psta_xlong	nrain	11	feet	1,415,898.725	1,605,935.466	1,503,451.089	(- to +) $1X10^{10}$	0
psta_ylat	nrain	11	feet	165,363.574	356,085.582	259,223.744	(- to +) $1X10^{10}$	0
rad_conv	one	1	none			1	0.1 – 100	1
rad_trncf	nhru	718	dec. frac.	0.819	0.959	0.874	0 –1	0.5
radadj_intcp	one	1	degree days			0	0 –1	1
radadj_slope	one	1	degree days / °F			0.5	0 – 1	0
radj_sppt	one	1	dec. frac.			0.44	0 – 1	0.44
radj_wppt	one	1	dec. frac.			0.5	0 – 1	0.5
radmax	one	1	dec. frac.			0.8	0.1 – 1	0.8
rain_mon	nhru X nmonths	8,616	inches	1.843	5.440	3.583	0 – 50	1
runoff_units	one	1	none			0	0 –1	1
sat_threshold	nhru	718	inches	2.071	5.701	4.712	1 – 999	999

Table 11. Summary of GSFLOW model parameters for Laurel Hill Creek Basin, southwestern, Pennsylvania, including dimensions, number of values specified, units, minimum, maximum, mean, the acceptable range, and default values for each parameter.—Continued

[If dimension was equal to one, the mean value is the one value used in the Laurel Hill Creek watershed model; dec. frac., decimal fraction; cal, calories; °C, degrees Celsius; >, greater than; °F, degrees Fahrenheit; gm, grams; cm^3, cubic centimeter]

Parameter	Dimension	Number of values	Units	Minimum	Maximum	Mean	Range	Default
settle_const	one	1	dec. frac.			0.5	0.01 – 0.5	0.1
slowcoef_lin	nhru	718	1/day	0.46	0.95	0.62	0 –1	0.015
slowcoef_sq	nhru	718	none	0	0	0	0 –1	0.1
smidx_coef	nhru	718	dec. frac.	0.000	0.094	0.004	0.0001 – 1	0.01
smidx_exp	nhru	718	1/inch	0.2	0.8	0.53	0.2 – 0.8	0.3
snarea_curve	ndeplval	44	dec. frac.	0.05	1	0.45	0 –1	1
snarea_thresh	nhru	718	inches	0	79.55	40.59	0 –200	50
snow_intcp	nhru	718	inches	0	0.016	0.004	0 –5	0.1
snow_mon	nhru X nmonths	8,616	inches	0	1.834	0.429	0 – 50	1
snowinfil_max	nhru	718	inches/day	3.506	3.525	3.519	0 – 20	2
soil_moist_init	nhru	718	inches	3.142	9.496	6.806	0 – 20	3
soil_moist_max	nhru	718	inches	3.801	13.795	10.565	0.001 – 20	6
soil_rechr_init	nhru	718	inches	3.064	6.401	4.785	0 – 10	1
soil_rechr_max	nhru	718	inches	3.450	9.236	7.401	0.001 – 10	2
soil_type	nhru	718	none	1	2	1.9	1 – 3	2
soil2gw_max	nhru	718	inches	0.038	0.071	0.041	0 –5	0
srain_intcp	nhru	718	inches	0	0.05	0.044	0 –5	0.1
ssr2gw_exp	nssr	718	none	1	1	1	0 –3	1
ssr2gw_rate	nssr	718	1/day	0.004	0.072	0.034	0 –1	0.1
ssstor_init	nssr	718	inches	0.314	2.294	1.499	0 – 20	0
szconverge	one	1	inches			0.000	0 – 0.1	0
temp_units	one	1	none			0	0 –1	0
tmax_allrain	nmonths	12	°F	36	36	36	0 – 90	40
tmax_allsnow	one	1	°F			20	-10 – 40	32
tmax_index	nmonths	12	°F	50	50	50	-10 – 110	50
tmax_mo_adj	nhru X nmonths	8,616	°F	-2.447	3.600	1.431	-10 – 10	0
tmin_mo_adj	nhru X nmonths	8,616	°F	-2.447	3.600	1.431	-10 – 10	0
transp_beg	nhru	718	month	4	4	4	1 – 12	4
transp_end	nhru	718	month	10	10	10	1 – 12	10
transp_tmax	nhru	718	degrees	350	350	350	0 – 1,000	500
tsta_elev	ntemp	9	feet	900	2000	1391	-300 – 30,000	0
tsta_xlong	ntemp	9	feet	1,415,898.725	1,605,935.466	1,499,852.413	(- to +) $1X10^{10}$	0
tsta_ylat	ntemp	9	feet	165,363.574	356,085.582	253,832.655	(- to +) $1X10^{10}$	0
tstorm_mo	nmonths	12	none	0	1	0.4	0 – 1	0
wrain_intcp	nhru	718	inches	0	0.042	0.021	0 –5	0.1

Parameter “ssr2gw_rate” controls the linear rate of gravity drainage from upper soil zones to PRMS reservoirs. Once the model is coupled in GSFLOW, the gravity drainage is to MODFLOW finite-difference cells. Increasing values for “ssr2gw_rate” increases groundwater flow and tends to decrease subsurface flow and surface runoff, which subsequently tends to increase the amount of water for base flow and reduce the peak and duration of stormflow events.

Note that the parameters in the *soilzone* module that were found to have a substantial effect on the simulated hydrograph also had to be modified once PRMS was coupled to MODFLOW in GSFLOW. This is primarily because, in the PRMS-only simulations, groundwater flow is primarily controlled by the parameter “gwflow_coef” in the PRMS module *gwflow*. The module *gwflow* controls how fast water moves from the PRMS groundwater reservoirs to the stream. Once coupled, MODFLOW dictates the groundwater-flow component of GSFLOW, and this necessitated the modification of parameter values in the *soilzone* module. The PRMS *gwflow* module is not used after PRMS is coupled to MODFLOW.

The module *srunoff_smidx_casc* computes surface runoff and infiltration for each HRU (table 8). The most important parameters included in this module are “carea_max,” “snowinfil_max,” “smidx_coef,” and “smidx_exp.” Two types of runoff occur in the model: Hortonian and Dunnian (Markstrom and others, 2008). Hortonian runoff from pervious parts of each HRU is related to the area in which throughfall and snowmelt exceed the soil-infiltration rate (Markstrom and others, 2008). Dunnian runoff is simulated from the soil zone in an HRU when storage as a volume per unit area in the preferential-flow reservoirs exceeds the depth defined by the saturation minus field-capacity thresholds (Markstrom and others, 2008). The parameter “carea_max” defines the maximum area for each HRU (as a decimal fraction of the total area) that could contribute surface runoff. Increasing the value for this parameter increases the surface runoff. The mean value for this parameter was about 0.09 for the basin. The “smidx” parameters are used in the algorithm to determine the amount of runoff from the contributing area. If values for “smidx” parameters are increased, values for “carea_max” would have to be decreased to keep the total amount of surface runoff static. The parameter “snowinfil_max” has a great effect on snowmelt events and the runoff associated with them. “Snowinfil_max” defines the daily maximum snowmelt infiltration for each HRU. Decreasing values for this parameter reduces the amount of snow infiltration, thus leading to more surface runoff.

The *cascade* module determines the computational order of the HRUs and groundwater reservoirs for routing flow downslope. The module was designed to route surface runoff and interflow from upslope HRUs to downslope HRUs (Markstrom and others, 2008). The flow from the upslope HRUs is cascaded to downslope HRUs where it can satisfy soil-zone storage capacities prior to being added as inflow to stream segments or lakes.

Groundwater - MODFLOW Model

Spatial and Temporal Discretization

A generalized model of the groundwater flow system was created for the Laurel Hill Creek Basin. The basin was divided into a finite-difference grid with 1 layer, 244 rows, and 94 columns. The extent of the active model grid is shown in figure 21. The layer type is specified as convertible, which means that a layer will automatically convert from confined to unconfined if the water table drops below the top of the layer. Model cells were 150 m by 150 m squares in the horizontal dimension. The model grid was constructed with rows oriented N 25^{o} E to align with the general strike of geologic units in the area. The active cells in the model are coincident with the area covered by HRUs in the PRMS model. Steady-state simulations were made to represent average groundwater levels, recharge, and groundwater discharge for 1991–2007. Changes caused by seasonal variations in recharge or pumping were not simulated in the steady-state MODFLOW model, but were incorporated in the MODFLOW-NWT input used in the coupled GSFLOW model. In the GSFLOW model, groundwater withdrawals, surface-water withdrawals, and discharges to surface water were varied by stress period on a monthly basis.

For this project, the objective of the MODFLOW model was to simulate the generalized interaction of the groundwater system with infiltration from land surface and streams. A more detailed, multi-layer groundwater model would be needed to simulate hydraulic heads and delineate contributing areas to wells in greater detail. Initially, a multi-layer model (8 layers) was developed for this study, but this was found to be very unstable with run to run variations evident with no change in parameterization. A 2 or 3 layer model would provide much better detail of the hydrogeologic framework of the system than a one-layer model; however, the simplified groundwater characterization (one layer model) was found to be necessary if a GSFLOW model was to be developed that would be numerically stable and could simulate the linked groundwater and surface-water flow problem in a reasonable amount of time.

Boundary Conditions

The elevation of the top of each cell was set to the mean elevation of land surface in the cell as determined from the USGS 30-meter DEM. Land-surface elevations assigned to the model cells ranged from 1,319 to 2,960 ft. The bottom of each model cell was set to 350 ft below the land-surface elevation, which corresponded to the approximate lower boundary of the active shallow groundwater flow system (McElroy, 2000). It was assumed that most of the groundwater flow that interacts with streams moves through the upper 350 feet of the aquifer.

The lateral extent of the modeled area was defined with no-flow boundaries. No-flow cells were placed around the perimeter of the modeled area on the topographic divide

Figure 21. Finite-difference grid with simulated streams, wells, and quarry pit withdrawal in the groundwater-flow model MODFLOW in the Laurel Hill Creek Basin, southwestern, Pennsylvania.

separating Laurel Hill Creek from adjacent basins. The lateral extent is coincident with that of the PRMS model, which is a necessary condition for linking the models in GSFLOW.

Infiltration from Precipitation

The MODFLOW-NWT model was constructed by assigning a spatially variable distribution of infiltration to the UZF package that was derived from the output of the PRMS simulations for 1991–2007. The infiltration rate from PRMS was computed as the sum of PRMS fluxes to groundwater (variables "soil_to_gw" and "ssr_to_gw") from each HRU and was assigned to MODFLOW cells on the basis of the percentage of each HRU in the cell. The simulated rate of infiltration from PRMS averaged 16.4 in/yr for the basin as a whole, which is reasonable when compared to the base flow for the same period of about 18 in/yr for streamflow records of the USGS streamflow-gaging station 03080000 Laurel Hill Creek at Ursina, Pa., computed by the use of the hydrograph-separation program PART (Rutledge, 1998).

Streams

Streams were simulated by use of the streamflow-routing (SFR2) package (Niswonger and Prudic, 2005), which allows streams to gain or lose water and accounts for the flow in each stream cell so that losses cannot exceed the simulated streamflow. The locations of streams simulated with SFR2 are shown in figure 21. Streams were represented by 243 segments made up of 2,423 reaches and included the simulation of unsaturated flow beneath the streams. The streambed top elevation in each SFR2 reach (model cell) was set equal to 2 meters less than the nearest elevation derived from the USGS 10-m DEM and was adjusted to ensure that the streambed elevation always decreased downstream. Thickness of the streambed was set to 1 m for all stream segments. Stream width was varied by segment on the basis of stream order from 3 m for first-order streams to 7 m for the lower reaches of Laurel Hill Creek. Hydraulic conductivity of the streambed was assigned a uniform value of 3 feet per day (ft/d). Stream slope for each segment was determined as the difference between the upstream and downstream elevations divided by segment length. Unsaturated-zone properties beneath all stream reaches were set to constant values. The saturated vertical hydraulic conductivity beneath streams was set equal to 3.3 ft/d, and the saturated water content was set equal to 0.011. Water was added at the upstream end of the stream segments in the SFR2 package to simulate major discharges to surface water and was subtracted to simulate major withdrawals of surface water. Three discharges totaling 0.27 ft^3/s and three withdrawals totaling 1.71 ft^3/s were simulated. Simulated withdrawals and discharges are listed in table 12, and sites are shown in figure 11.

Evapotranspiration

Evapotranspiration from groundwater was simulated with the UZF package. A uniform potential evapotranspiration rate of 23.4 in/yr derived from a preliminary simulation from PRMS was used for all model cells. An extinction depth of 5 ft below land surface was assumed. When linked to the GSFLOW model, the potential evapotranspiration from MODFLOW-NWT is replaced by values for each HRU computed by PRMS on the basis of daily climate conditions.

Wells and Drains

Groundwater withdrawals from 15 wells in the Laurel Hill Creek Basin (table 13; fig. 21) were simulated in the steady-state model by use of the well package in MODFLOW-NWT. All withdrawals from public-supply wells were simulated (regardless of rate) along with withdrawals for commercial, industrial, and agricultural uses that exceeded 10 gallons per minute (gal/min). Average simulated groundwater withdrawals for 1991–2007 from the model are shown in table 13. The total groundwater-withdrawal rate simulated from 15 wells in the Laurel Hill Creek Basin was 528.6 gal/min.

The drain package was used to simulate groundwater draining into the south pit of a quarry at row 49, column 24 of the model (see fig. 21 for actual location). The elevation of the drain was 762 m, which is the approximate water level maintained by the quarry operator.

Aquifer Properties

Aquifer properties were assigned in the Upstream Weighting (UPW) Package of the steady-state MODFLOW-NWT model. Parameters were used to represent the spatial distribution of hydraulic conductivity for the geologic units according to topographic position. Hydraulic conductivity for all geologic units was assigned a value of 0.08 meters per day (m/d) in upland areas and 1.0 m/d in valleys. The specific yield for upland areas was set at 0.0003 (dimensionless) and for valley settings was set at 0.003. The greater values were assigned to valley settings because a previous study indicated well yields in Somerset County were greater in valleys than in uplands (McElroy, 2000). The distribution of hydraulic-conductivity values is shown in figure 22. The ratio of hydraulic conductivities along model columns and along model rows (HANI) was assumed to equal 1.0.

Hydraulic properties of the unsaturated zone were assigned in the UZF Package. Values of saturated vertical hydraulic conductivity were set equal to the hydraulic conductivity for the saturated zone—0.08 m/d for upland areas and 1.0 m/d in valleys.

Table 12. Summary of discharges to, and withdrawals from, surface water simulated in the SFR2 streamflow-routing package of the steady-state groundwater model for the Laurel Hill Creek Basin, southwestern, Pennsylvania.

Surface-water site identifier and description	Location in model		Rate of discharge or withdrawal	
	Row	Column	(cubic meters per day)	(cubic feet per second)
Discharge sites				
DISCH04 – outfall	104	48	212	0.09
DISCH05 – outfall	131	57	28	0.01
DISCH06 – quarry	46	19	409	0.17
Withdrawal sites				
WDRW_SP1 – hemlock	75	24	133	0.05
WDRW_SW1 – gosling lake	98	33	171	0.07
WDRW_SW2 – laurel hill	52	57	3,886	1.59

Table 13. Groundwater withdrawals from wells simulated in the MODFLOW_NWT steady-state model for the Laurel Hill Creek Basin, southwestern, Pennsylvania.

Well identifier	Model location		Mean withdrawal rate, 1991–2007	
	Row	Column	(cubic meters per day)	(gallons per minute)
Gosling Well	97	32	832.2	153.8
Shafer Run Well 2	35	42	746.3	137.9
Hidden Valley Well 1	49	30	513.4	94.9
Shafer Run Well 1	37	47	245.9	45.5
SWA Meyer Well (Well 3)	52	56	229.1	42.3
COMM41	56	33	153.2	28.3
AG18	50	78	69.30	12.8
PIO orchard well (1)	67	58	26.83	5.0
NE well 1	45	27	20.18	3.7
LHSP Wellhouse 2	81	36	16.82	3.1
PIO overflow well 3	64	55	3.37	0.6
PIO bathhouse well 2	63	58	1.60	0.3
LHSP well4	81	58	1.11	0.2
Hidden Valley well 2	50	28	0.80	0.1
LHSP well 3	92	66	0.57	0.1

MODFLOW Steady-State Calibration

Hydraulic conductivity values in the MODFLOW-NWT model were adjusted to approximate the mean groundwater levels in 17 wells (site locations in fig. 10) sampled during the groundwater synoptic sampling in 2007. Hydraulic conductivity values initially obtained from the automated parameter-estimation program UCODE-2005 (Poeter and others, 2005) were adjusted by trial and error to arrive at the calibrated values described in section "Aquifer Properties." Low values of estimated hydraulic conductivity from the UCODE-2005 program caused groundwater levels to be higher than land surface in many areas, so it was necessary to manually increase hydraulic conductivity until the water level was lowered. As a result, the simulated water levels were generally lower than observed levels, and for upland wells near basin divides, the model substantially underestimated groundwater levels compared to observed levels. The observed and simulated groundwater levels for this study from each of the 17 wells in the Laurel Hill Creek Basin are given in table 14. The simulated water table is illustrated in figure 23.

The underestimation of groundwater levels in the steady-state model illustrates a limitation of the model. This limitation was caused mostly by the use of a single model

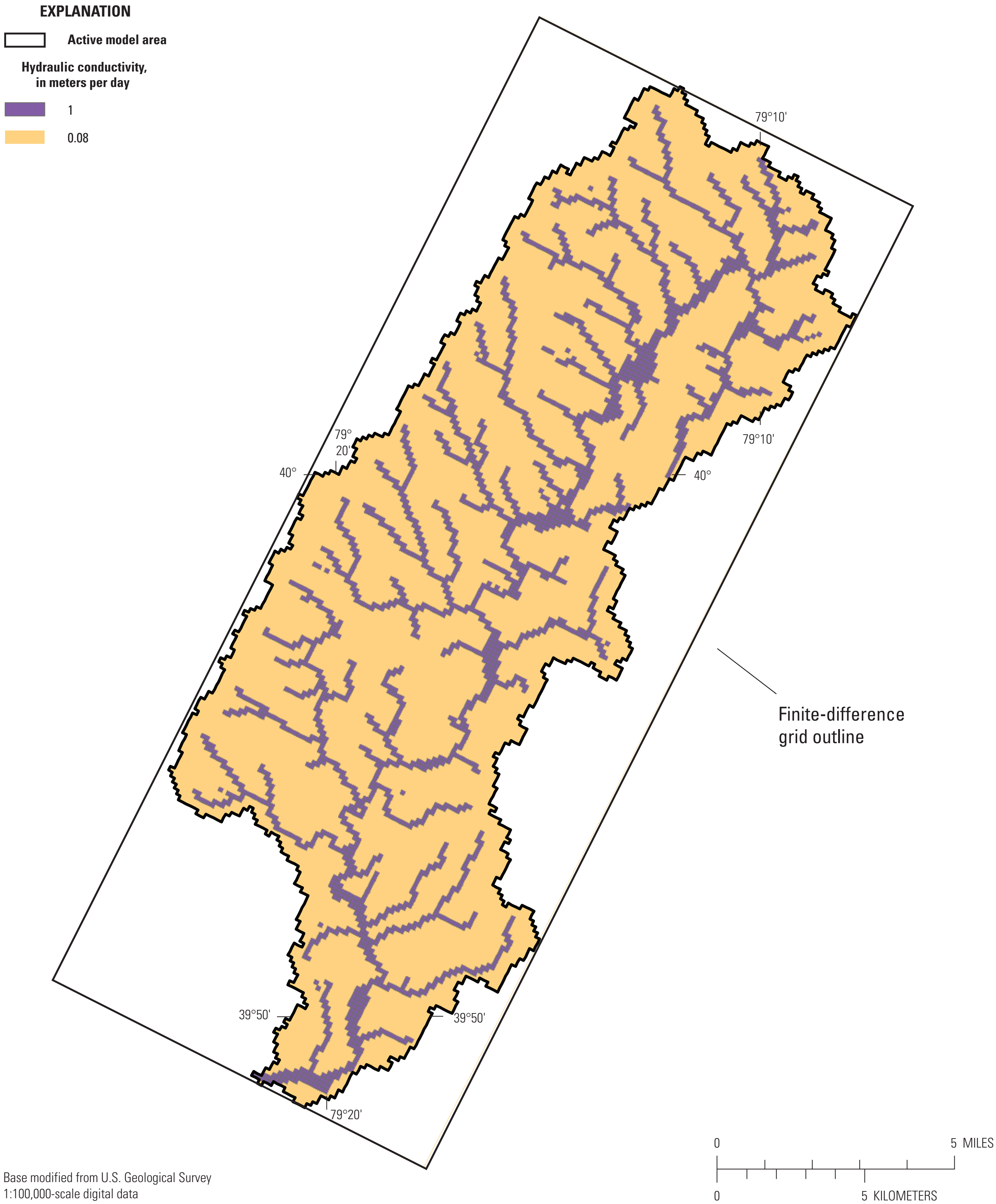


Figure 22. MODFLOW grid with the distribution of hydraulic conductivity values assigned to the steady-state groundwater-flow model for the Laurel Hill Creek Basin, southwestern, Pennsylvania.

Table 14. Observed (July and October 2007) and simulated water levels at groundwater wells used to adjust the steady state groundwater-flow model (MODFLOW) for the Laurel Hill Creek Basin, southwestern, Pennsylvania.

[USGS, U.S. Geological Survey]

USGS well identifier	Location in MODFLOW grid		Water-level altitude, in meters		
	Row	Column	Observed [1]	MODFLOW simulated	GSFLOW simulated [2]
FA 510	150	6	789.72	742.14	701.68
SO 856	113	52	566.21	574.37	573.53
SO 857	78	68	669.24	665.06	617.51
SO 858	150	56	517.14	517.88	517.63
SO 859	13	65	640.50	635.59	628.80
SO 860	39	55	644.24	624.68	619.86
SO 861a [3]	37	46	641.15	655.62	655.17
SO 861b [3]	35	41	673.12	669.22	670.12
SO 862	58	17	858.39	789.93	761.76
SO 863	81	57	650.49	610.33	600.24
SO 864	139	16	734.51	703.27	671.56
SO 865	132	36	583.76	586.21	586.60
SO 867	23	65	657.17	623.41	617.68
SO 868	117	61	599.22	582.64	566.93
SO 869	224	68	410.27	413.06	411.71
SO 870	97	32	647.89	646.70	646.52
SO 872	175	71	587.36	594.29	564.27

[1] Observed water level is the mean of two measurements made in July and October 2007.

[2] Simulated water levels are mean values for the date sampled in July 2007 and for September 29, 2007, which is last day of simulation in GSFLOW model.

[3] SO 861a and SO 861b are two wells owned by a water authority. Water from both these wells was sampled at the water authority building and identified SO 861 as the sampled well. The two wells are near each other in the basin, and water levels were obtained for both wells.

layer to represent the groundwater-flow system of the study area, which is an area of high relief underlain by layered sedimentary rocks that impart a high ratio of horizontal to vertical anisotropy with respect to hydraulic conductivity. In the upland areas, the large vertical hydraulic gradients needed to move groundwater downward cannot be simulated with a one-layer model; however, multi-layer models were found to be numerically unstable (because of problems with cells wetting and drying), so a one-layer model was used. The one-layer model allowed groundwater/surface-water interaction to be simulated but limited the ability to accurately reproduce groundwater levels in upland areas. The two wells (SO 862 and FA 510) with the greatest difference between observed and simulated water levels also had the two highest elevations for any wells sampled (table 14 and appendix 4), with both of the wells along the ridge that is the western boundary of the watershed (fig. 10).

GSFLOW–Linkage of PRMS and MODFLOW

The linkage of PRMS and MODFLOW in GSFLOW requires calibration of the model even though both PRMS and MODFLOW were independently calibrated prior to the linkage. The main reason for this is that processes defined with PRMS and MODFLOW within the stand-alone calibrations are replaced by coupled processes simulated by GSFLOW. The PRMS *gwflow* module is not necessary in the coupled model since MODFLOW defines the groundwater processes. The groundwater reservoirs in PRMS are replaced by the finite-difference cells defined within MODFLOW. For MODFLOW, the ET that was used for the stand-alone model was replaced by the daily ET values generated by the *potet_jh* module in PRMS. Specific yields and hydraulic conductivities are defined in MODFLOW. MODFLOW-defined heads

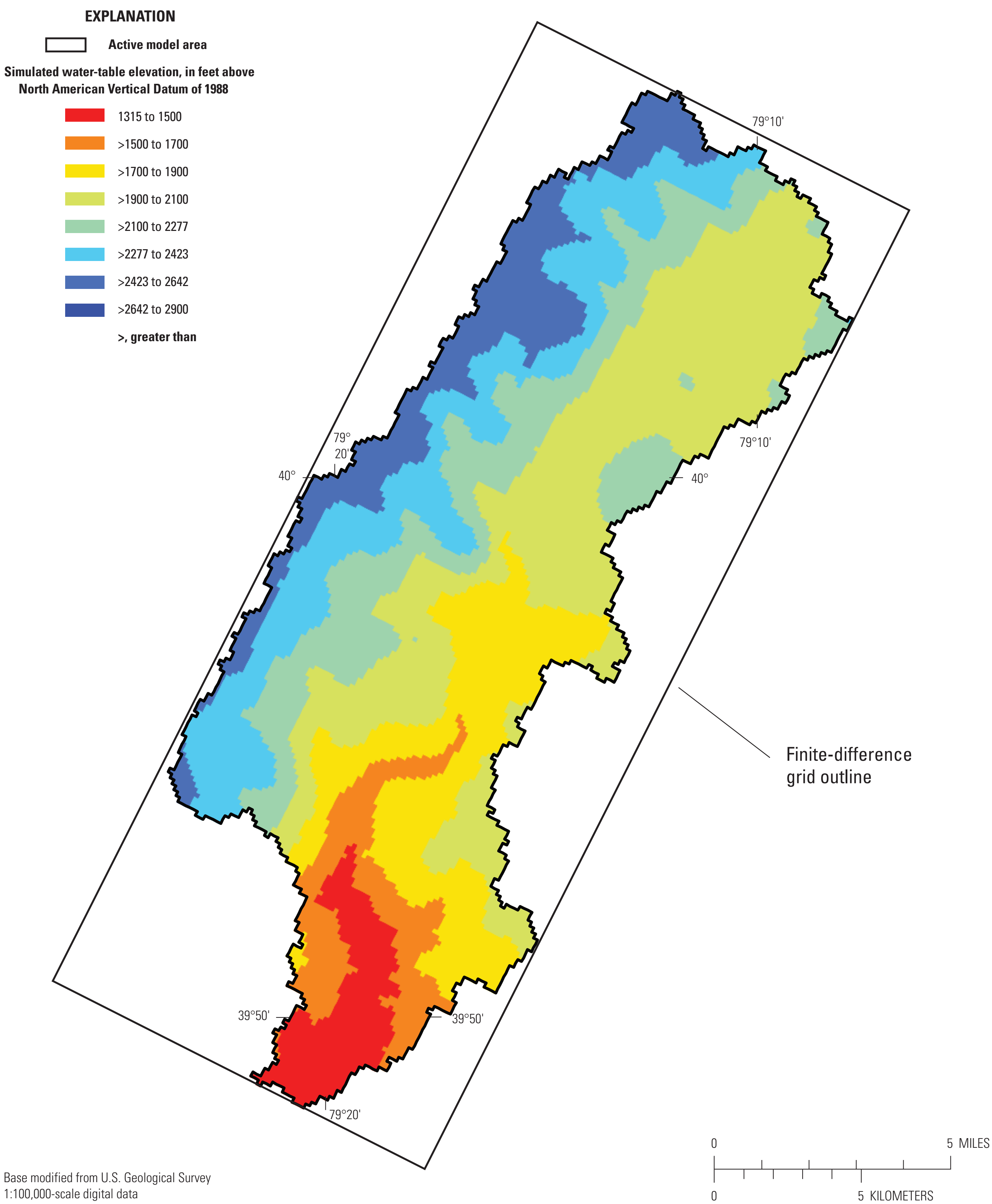


Figure 23. Simulated steady-state water table for the steady-state groundwater-flow model for the Laurel Hill Creek Basin, southwestern, Pennsylvania.

and hydraulic conductivities for the saturated and unsaturated zones interact with PRMS computations for the soil zone once the models are coupled. In the coupled model, MODFLOW receives daily and spatially distributed gravity drainage from PRMS, replacing the gravity drainage in the MODFLOW-only simulations. MODFLOW tends to reject some of the gravity drainage provided by PRMS soil-zone processes, and this causes a delay in water reaching the stream (R. Steven Regan, USGS, written commun., 2012). The coupled GSFLOW model has three soil zone reservoirs (preferential flow, gravity, and capillary) that occupy the same physical space but represent different processes. Rejected gravity drainage initially is stored in the gravity reservoir where it either stays or moves to one of the other reservoirs, or it becomes interflow or surface runoff (Markstrom and others, 2008). The SFR2 package in MODFLOW computes streamflow in the coupled model; therefore, the streamflow from the PRMS-only simulations is replaced by the MODFLOW generated streamflow.

GSFLOW Model Results

For calibration of the GSFLOW model, the hydraulic-conductivity values were modified from the initial values in MODFLOW, and the parameter values for the *soilzone* module were modified from the initial values in PRMS. Hydraulic conductivities for upland areas in MODFLOW were increased from 0.08 m/d to 1–2 m/d, whereas the hydraulic conductivity for valleys was reduced from 1 m/d to 0.5 m/d. The vertical hydraulic conductivity for the saturated zone was increased to 3.5 m/d for the entire basin. This tended to allow for more rapid downward movement of water in the basin, but once the water flowed into the valleys and near the stream channel, the discharge to the stream network was slowed to allow a more gradual movement of water over time into the stream segments. These changes to MODFLOW parameters were iteratively applied in coordination with changes to PRMS parameters. The PRMS parameters that changed significantly with the coupled model were “pref_flow_den,” “slowcoef_lin,” and “soil2gw_max.” Mean values for “pref_flow_den” (decimal fraction of the soil zone available for preferential flow) decreased from 0.64 in the uncoupled model to 0.07 in the coupled model. Mean values for “slowcoef_lin” (flow routing coefficient for slow interflow) increased from 0.02 to 0.62 in the coupled model, and mean values for “soil2gw_max” (maximum value of soil-water excess routed to groundwater reservoirs) decreased from 0.49 to 0.04 in the coupled model. These changes to PRMS parameters basically reduced the rapid movement of water to streams via fast interflow by reducing the available pore space for fast interflow. This repartitioned water into slow interflow, which mimicked the changes to the MODFLOW parameters.

The GSFLOW calibration of the coupled models for the Laurel Hill Creek Basin was driven primarily by balancing the water budget for the entire period and secondarily by acquiring the best fit to low-flow periods as opposed to periods dominated by stormflow. If the total volume of water modeled for the study period closely approximated (was within about 0.1 percent) the observed streamflow, then hydrograph comparisons between observed and simulated values were manually reviewed to determine whether the change in parameterization improved model simulations. Groundwater levels were not considered in the GSFLOW calibration process. The model was calibrated to streamflow for the time period from January 1, 1991, to September 29, 2007.

Water Budget

The summations of the observed streamflow at the Laurel Hill Creek at Ursina, Pa., streamflow-gaging station (03080000) and the simulated streamflow for Ursina were very close over the entire modeled period; however, the year to year variations showed a wide range of percent differences between observed and simulated streamflow (table 15). The difference between the observed and simulated streamflow for the entire period was only 0.1 percent. Excluding the 1991 water year due to model start up issues and only 9 months of data, the year to year variations in observed and simulated flow ranged from -27 to 24 percent with 9 of the years having less than a 10-percent difference between observed and simulated streamflows.

The simulated water budget for the basin over the entire period (1991–2007) yielded an annual average estimated precipitation of 45.6 in. This water was allocated on an average annual basis to simulated streamflow (29.5 in.), ET (15.5 in.), water use (0.3 in.), and groundwater flow out of the basin (0.1 in.) (table 15). Any remaining water was distributed to storage compartments. The average precipitation estimated for the entire basin was a very good approximation of the regional annual precipitation average. The overall average observed precipitation for the Laurel Hill Creek Basin from 1971 to 2000 was 48 in/yr (PRISM Climate Group, Oregon State University, 2011), so the precipitation for 1991–2007 was estimated to be slightly below the average annual precipitation amount for the area. The observed annual streamflow yield for Laurel Hill Creek at Ursina, Pa., averaged 29.5 inches for 1991–2007. The GSFLOW-simulated annual ET for the basin (15.5 in.) is less than the annual estimated ET values (range of 18–21 in/yr) derived by Sanford and Selnick (2013) for the region. The estimated water use in the basin (0.3 in/yr) equates to an average annual use of about 690 million gallons per year. The simulated groundwater loss of 0.1 in/yr is along the basin boundary to the saturated zone. This groundwater loss was consistently evident for many model scenarios.

The simulated flow to the stream was distributed between groundwater, subsurface, and surface runoff. Confounding the percent contributed by each source is the fact that the model determined some of the water getting to the stream was lost from the stream through the streambed (table 15). The groundwater, subsurface, and surface runoff components of the total flow to the stream account for 25, 62, and 13 percent, respectively; therefore, the GSFLOW model has most of the streamflow originating from the subsurface component. Compared to

Table 15. Observed streamflow and GSFLOW simulated components of the water budget for the Laurel Hill Creek Basin, southwestern, Pennsylvania, 1991–2007. Simulation was for January 1, 1991, to September 29, 2007.

[All units are in inches over the entire watershed, unless otherwise noted; PART, hydrograph separation program used to partition base flow and stormflow; ET, evapotranspiration]

Water year	Observed streamflow	PART base flow, in percent	Simulated streamflow	Simulated precipita-tion	Simulated ET	Simulated ground-water	Simulated subsurface flow	Simulated surface runoff	Simulated streambed loss	Simulated ground-water loss from basin	Estimated water use (input to model)
1991	19.59	72.3	10.29	26.86	16.16	4.71	7.21	1.27	2.65	0.05	0.21
1992	22.75	73.1	28.23	43.28	12.52	8.36	20.57	4.17	4.51	0.07	0.28
1993	28.12	65.1	28.71	44.73	14.98	8.48	20.72	4.33	4.44	0.07	0.30
1994	37.30	62.5	34.27	48.05	13.95	9.14	25.18	4.95	4.62	0.17	0.40
1995	21.16	73.8	20.68	34.28	15.59	7.86	15.24	1.96	4.12	0.17	0.34
1996	43.24	57.2	39.23	57.10	14.47	9.13	28.59	6.72	4.89	0.14	0.34
1997	30.67	63.3	29.30	44.02	14.28	8.66	20.44	4.98	4.45	0.14	0.35
1998	32.00	61.3	31.77	46.87	15.31	9.49	23.09	4.13	4.65	0.15	0.33
1999	21.41	62.1	19.06	35.01	15.71	7.03	14.00	2.14	3.89	0.17	0.32
2000	26.95	58.1	33.34	49.13	14.78	8.87	24.22	5.24	4.66	0.14	0.35
2001	22.77	66.7	21.21	37.77	16.50	7.60	15.73	2.27	4.12	0.12	0.30
2002	23.34	62.8	28.00	45.70	17.19	8.09	20.36	4.08	4.30	0.13	0.29
2003	36.85	66.3	41.11	58.31	16.37	9.64	29.51	7.05	4.79	0.12	0.31
2004	41.15	52.5	45.23	60.43	15.08	10.03	30.26	10.22	4.95	0.10	0.30
2005	31.28	59.5	22.71	37.55	16.63	8.32	16.52	2.39	4.21	0.09	0.29
2006	25.69	60.7	29.45	46.82	14.56	8.62	21.68	4.04	4.54	0.09	0.31
2007	29.58	62.3	31.79	47.90	16.31	8.73	22.31	5.50	4.40	0.10	0.33
Total	493.85	62.6	494.38	763.81	260.39	142.76	355.63	75.44	74.19	2.02	5.35

other studies, the percent of subsurface flow for this study was somewhat high. Bent and others (2011) used the Hydrologic Simulation Program – Fortran (HSPF) Precipitation-Runoff model for a New England setting that is not as mountainous or forested as the Laurel Hill Creek Basin and generated a model that estimated the total flow partition of 74, 17, and 9 percent, for groundwater, subsurface flow, and surface runoff, respectively. Bjerklie and others (2010) used PRMS to model the Pomperaug River Basin in Connecticut, which is primarily forested but not as steep as the Laurel Hill Creek Basin. They estimated a total flow partition of 58, 27, and 15 percent, for groundwater, subsurface flow, and surface runoff, respectively.

The model partitions the subsurface flow (interflow) into slow flow (micropore) and fast flow (preferential or macropore) components. Slow and fast interflow through the subsurface is routed either directly to the stream or to groundwater. For the Laurel Hill Creek Basin model, most of the simulated subsurface flow that reached the stream was in the form of slow flow. The final model simulation indicated that 97 percent of the subsurface flow was slow flow and only 3 percent was preferential flow. The proportion of slow to fast flow is highly dependent on the parameter “pref_flow_den.” The mean value for “pref_flow_den” for this model is 0.07, which is a low value considering the acceptable range is 0–1. A value of 0.07 yields a very low density of preferential flow space in the soil zones in the model. Higher “pref_flow_den” values increase macropore flow with a subsequent decrease in simulated ET. Lower “pref_flow_den” values help to keep water in the upper part of the soil zone, which promotes increased evapotranspiration losses. For this basin, low “pref_flow_den” values were required to keep evapotranspiration losses in the 15–16 in range so that the simulated flow for the entire period was similar in magnitude to the observed flow. The simulated surface runoff was partitioned between Dunnian and Hortonian runoff. Dunnian runoff occurs when storage in the preferential flow reservoirs exceeds saturated conditions and Hortonian runoff occurs when precipitation or snowmelt exceeds soil infiltration rates. Sixty-five percent of the simulated surface runoff was Dunnian runoff, and 35 percent was in the form of Hortonian runoff. Melting snow is an important contributor to groundwater recharge and streamflow in the basin. The simulated snowmelt in the basin generated about

15 percent of the total streamflow. The snowmelt was transported to the stream via surface-runoff processes or infiltrated the soil and was transmitted as interflow or groundwater base flow to the stream.

Simulated Hydrograph Analysis

The simulated daily streamflow for GSFLOW and the observed daily streamflow from the streamflow-gaging station at Laurel Hill Creek at Ursina, Pa., are presented for the entire model period (fig. 24). The initial simulated values for the first year of the model period show that the model took a few months to adjust to a relatively steady-state condition related to initial storage terms being developed in PRMS (Markstrom and others, 2008). This “start up” period is typical for the model (R. Steven Regan, USGS, written commun., 2012). The start up period can take as long as a few years, but this is somewhat dependent on the length of the model period and the accuracy of the parameterization. The residual plot (observed minus simulated values; fig. 25) shows that there is a seasonal variation in the residuals. Simulated streamflows for winter months tend to have most of the positive residuals, whereas simulated streamflows for summer months tend to have most of the negative residuals (fig. 25). Modeled ET was reduced to zero for simulated conditions during the winter, so the higher observed flows in winter were not due to ET error. It is likely that the routing of snowmelt water for simulated conditions was being held in the subsurface when more of it should have been routed to the stream via surface runoff. It is not possible to simulate a frozen ice layer in the subsurface that would tend to decrease infiltration and promote more surface runoff. This simulated snowmelt that was held in the subsurface discharged to the stream gradually during the summer months, and this tended to cause simulated flows in summer to exceed observed flows.

The observed streamflow at the Laurel Hill Creek at Ursina, Pa., streamflow-gaging station was analyzed to determine the percentage of base flow for the period from January 1, 1991, through September 29, 2007 (table 15). Daily values were entered as input to the PART program. PART uses streamflow partitioning to estimate a daily record of groundwater discharge from daily values of streamflow. The method designates groundwater discharge to be equal to streamflow on days that fit a requirement of antecedent recession or linearly interpolates groundwater discharge for other days (Rutledge, 1998; U.S. Geological Survey, 2013). The PART program uses a similar method for streamflow partitioning to that of Shirmohammadi and others (1984) in that base flow is generally inclusive of both groundwater and subsurface flow to the stream.

The daily observed streamflow at Ursina, Pa. (station 03080000), for 1991–2007 was separated into predominantly base-flow days and predominantly stormflow days using PART. Once the observed data were classified by flow, the simulated GSFLOW values for the period were merged into the data set. The GSFLOW model runs were calibrated to reduce differences between observed and simulated flows primarily during low-flow periods. Approximately 63 percent of total flow at the Laurel Hill Creek at Ursina, Pa., streamflow-gaging station from January 1, 1991, through September 29, 2007, was base flow according to PART results. GSFLOW estimated that 87 percent of the total flow during the period was groundwater and subsurface flow (table 15). Only about 15 percent of the daily values over this period had streamflow that was estimated by PART to be less than 50 percent base flow. So, of the 6,116 days of the model period, only 895 days had daily flow that was estimated to be primarily (greater than 50 percent) stormflow. The percent difference in model residuals tended to decrease with an increase in the percentage of estimated PART base flow using the daily values for the model period (fig. 26). The highest percent differences were evident for days with less than 10 percent base flow, and the lowest percent differences were evident for days with 100 percent base flow (table 16).

The results from the PART analysis of observed and simulated daily streamflow values indicate that the GSFLOW model calibrated for the Laurel Hill Creek Basin for 1991–2007 provided more accurate simulated daily streamflow values for days when observed streamflow for Laurel Hill Creek at Ursina, Pa., was predominantly identified as base flow by PART than for days when observed streamflow had a higher proportion of stormflow as identified by PART. The objective of GSFLOW model development was to provide a tool to simulate changes in streamflow for future water-use and land-use scenarios. The magnitude of water use in

Table 16. Mean and median percent differences between observed and simulated (GSFLOW) daily streamflows, by percent base-flow estimates, derived by the PART program for the Laurel Hill Creek at Ursina, Pennsylvania, streamflow-gaging station (03080000), January 1, 1991, through September 29, 2007.

[<, less than]

Percent base flow	Percent difference	
	Mean	Median
0 – <10	263	117
10 – <20	235	70
20 – <30	205	71
30 – <40	175	71
40 – <50	208	65
50 – <60	154	63
60 – <70	180	69
70 – <80	170	69
80 – <90	148	64
90 – <100	149	62
100	99	55

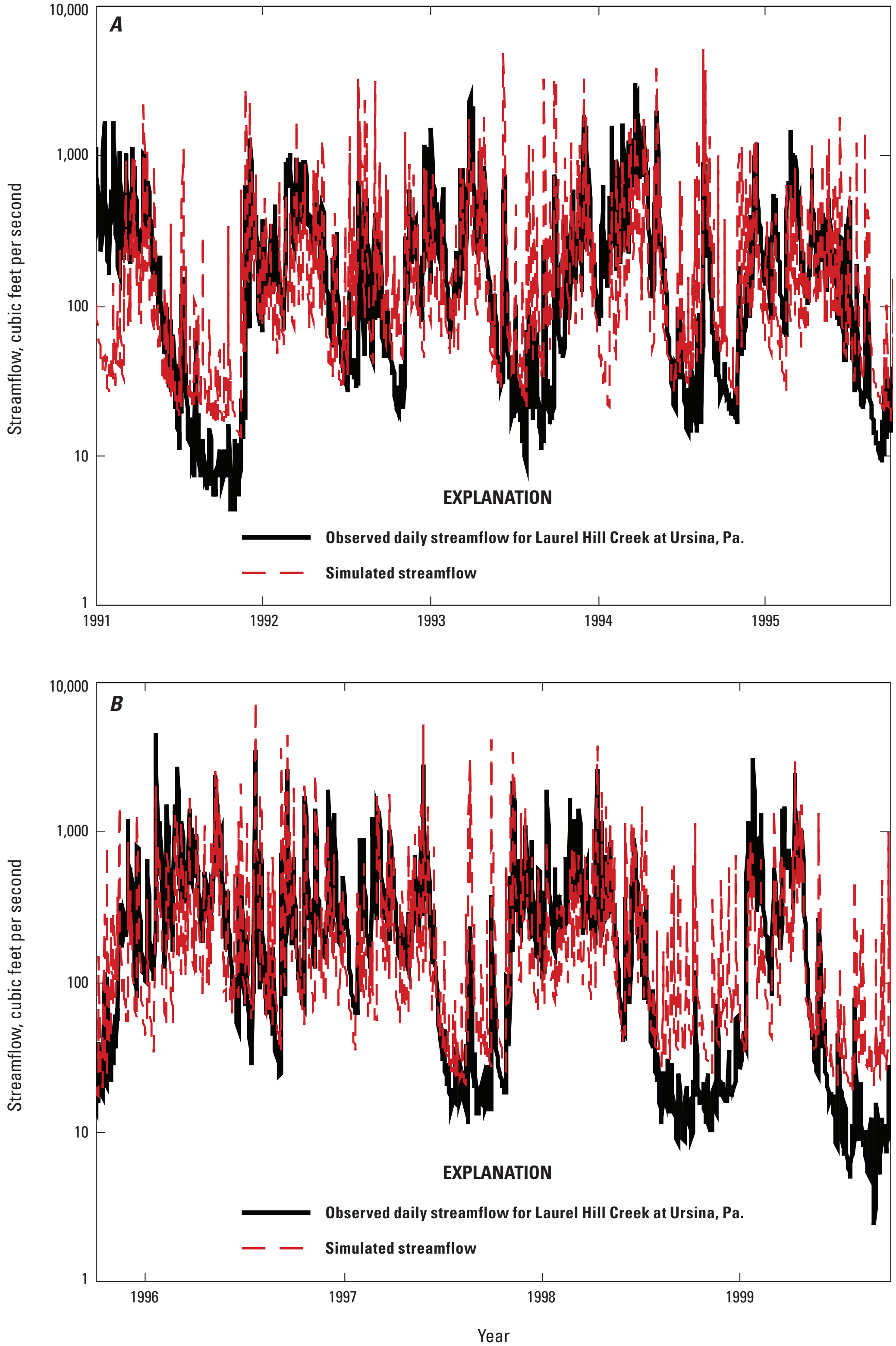


Figure 24. Time series plots of observed daily streamflow at the Laurel Hill Creek at Ursina, Pennsylvania, streamflow-gaging station 03080000 and simulated streamflow from the GSFLOW model for the Laurel Hill Creek Basin, southwestern, Pennsylvania: *A*, 1991–95, *B*, 1996–99, *C*, 2000–03, and *D*, 2004–07.

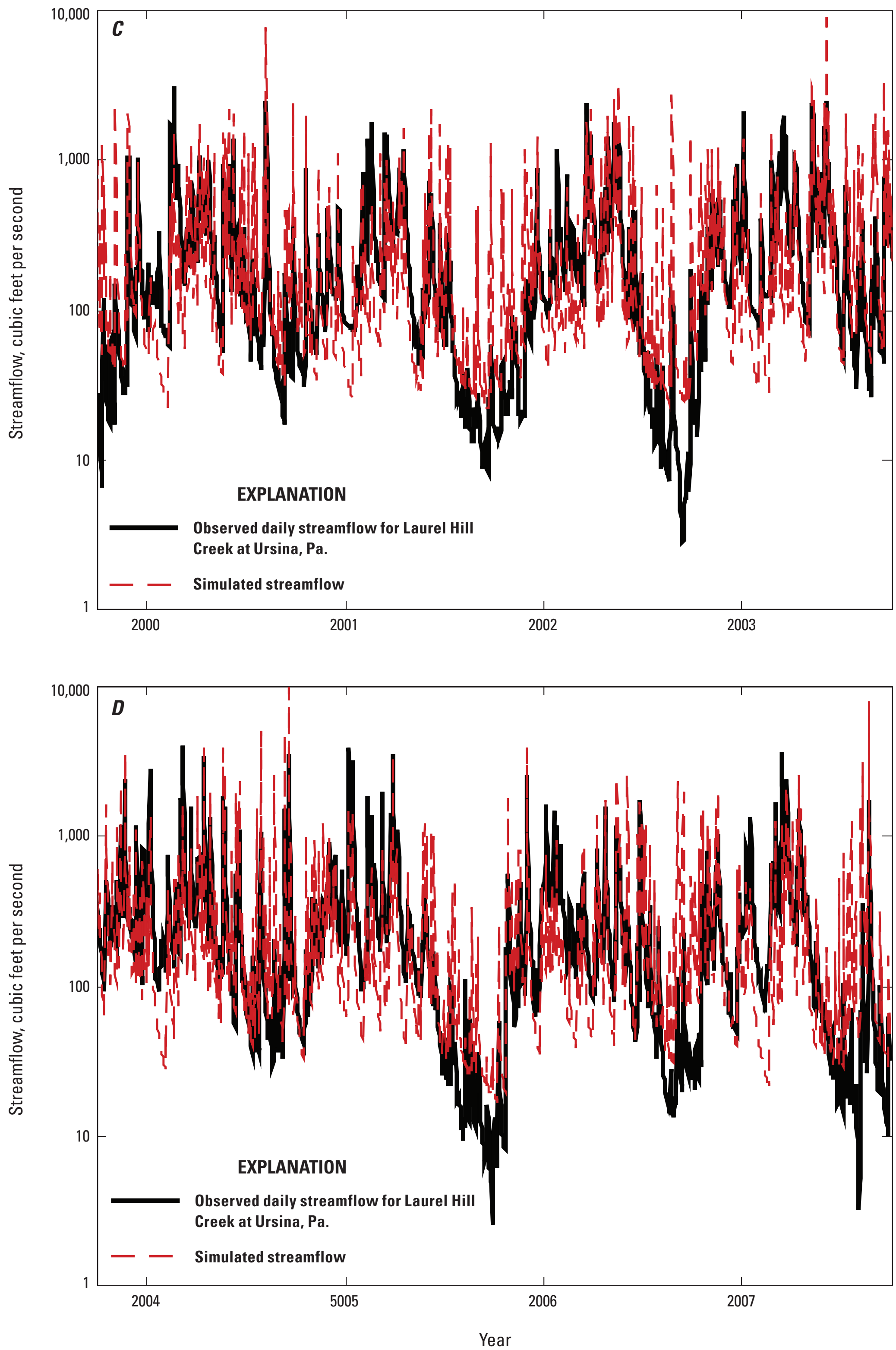


Figure 24. Time series plots of observed daily streamflow at the Laurel Hill Creek at Ursina, Pennsylvania, streamflow-gaging station 03080000 and simulated streamflow from the GSFLOW model for the Laurel Hill Creek Basin, southwestern, Pennsylvania: *A*, 1991–95, *B*, 1996–99, *C*, 2000–03, and *D*, 2004–07.—Continued

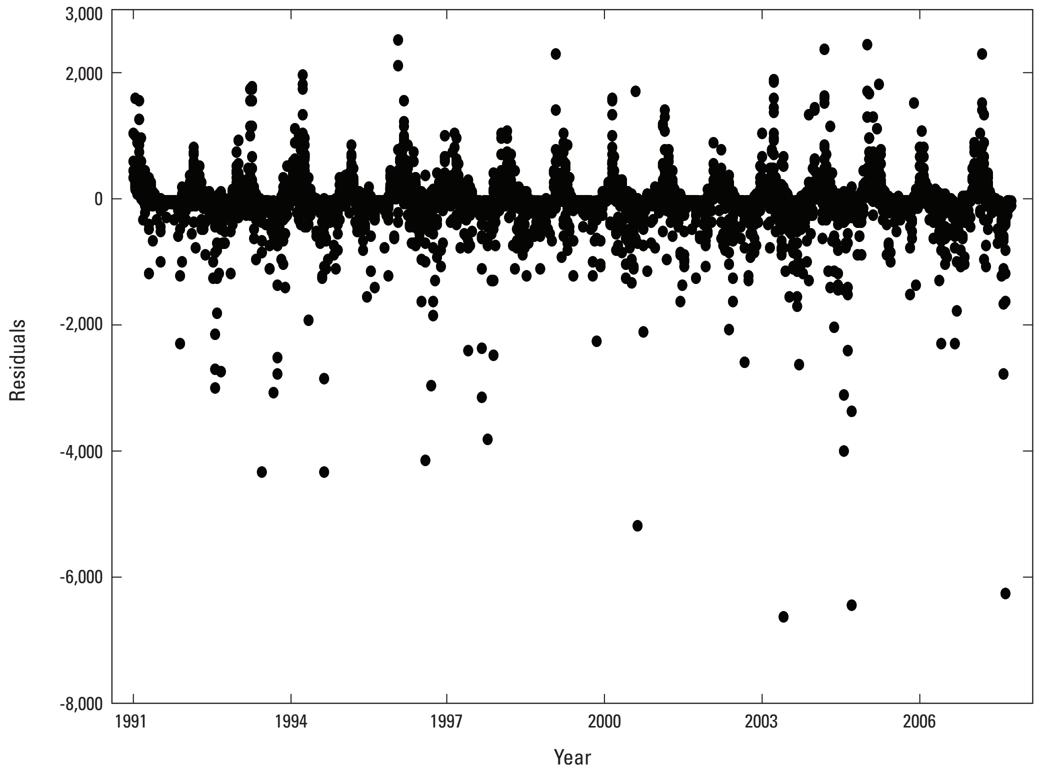


Figure 25. Time series plot of the residuals (observed minus simulated streamflow) for Laurel Hill Creek at Ursina, Pennsylvania, station 03080000 from the GSFLOW model for January 1, 1991, through September 29, 2007.

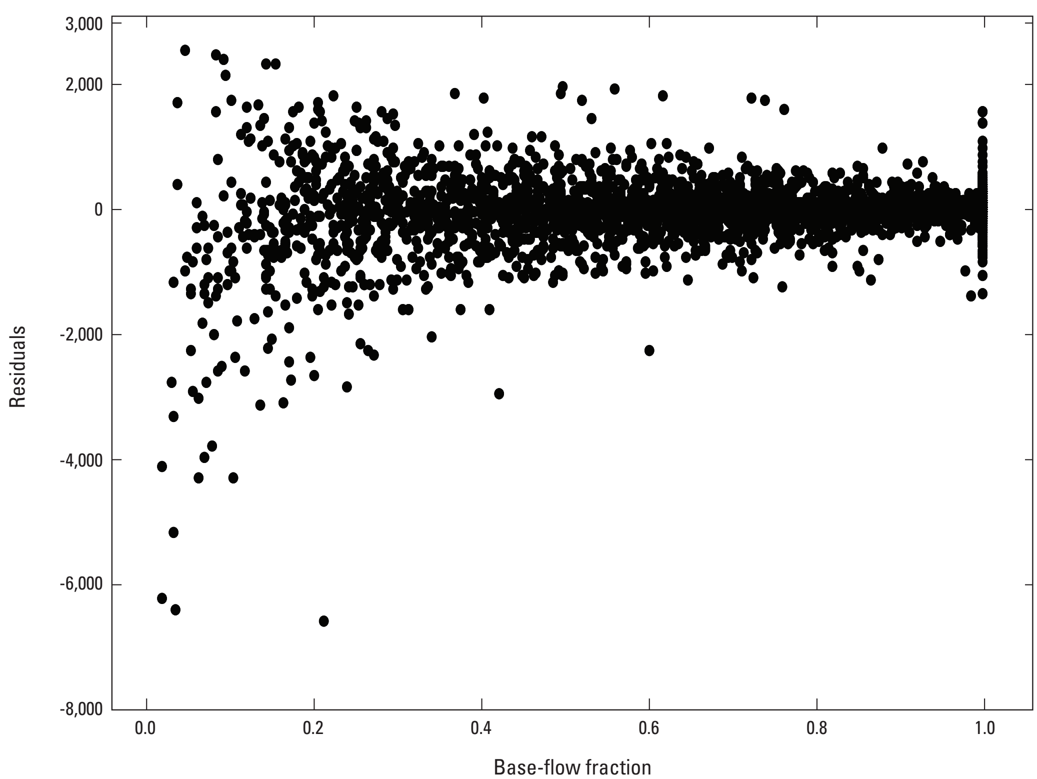


Figure 26. Residuals from the GSFLOW model (observed minus simulated streamflow values) for January 1, 1991, through September 29, 2007, in relation to the daily base-flow fraction, as derived by the hydrograph separation program PART for the Laurel Hill Creek at Ursina, Pennsylvania, streamflow-gaging station (03080000).

the Laurel Hill Creek Basin is not relevant during periods when streamflow is augmented by storm events or snowmelt; therefore, the emphasis for this study was low-flow conditions. Even though GSFLOW was calibrated with an emphasis on reducing model residuals for low-flow conditions, model accuracy during low-flow conditions could be improved by enhancing the MODFLOW component of the coupled GSFLOW model from a 1-layer approximation of the groundwater flow system to a 2- to 3-layer representation.

GSFLOW Model Results and Water Quality

The GSFLOW model estimates that the majority of flow in the main stem of Laurel Hill Creek originates from the subsurface component, with the secondary source being groundwater, then surface runoff. This model result seems consistent with the water-quality data collected in 2007, which indicates that many tributaries along the western half of the basin had low pH and SC values, indicating poorly buffered water and relatively short flow paths from precipitation inputs to eventual outflow to a stream channel. Tributaries draining the western ridge retain characteristics of the original acidic precipitation because the runoff and shallow interflow that sustains streamflow moves through highly weathered rock that lacks buffering or acid-forming minerals. The low SO_4 concentration in the tributaries (mean concentration of 10 mg/L) indicates acid-forming minerals are not prevalent in the subsurface weathered materials.

Near-neutral stream samples are present in the main stem of Laurel Hill Creek, and higher alkalinity in the main stem relative to tributary sites indicates that groundwater inflows to the main stem contribute alkalinity. This indicates that the main stem receives a higher proportion of deeper groundwater flow than the tributaries. Mineralization occurs along the deeper flow paths with some of this water eventually discharging to the main stem. The higher specific conductance in the main stem is more reflective of road salt applications, which are transported to the main stem via subsurface/runoff processes.

Another characteristic of the water-quality samples which parallels results from the GSFLOW model are the differences in well and spring water. Groundwater from wells tends to have higher concentration of dissolved ions than springs because of more extensive interactions with aquifer minerals along deeper flow paths to wells, compared to the springs that generally originate from waters that travel along shallow, shorter flow paths. The mean SC for wells and springs sampled in 2007 was 180 and 63 µS/cm, respectively. The springs directly contribute to the streamflow in the tributaries and the main stem. One spring sampled in 2007 yields 68 gallons per minute (appendix 4) to the receiving tributary along the western ridge. Springs are numerous in the basin and this input of water to the main stem would be considered a subsurface contributor of water to the main stem.

Summary and Conclusions

A study was conducted by the U.S. Geological Survey, in cooperation with Somerset County Conservation District, to characterize water quality and quantity, and to simulate groundwater flow, in Laurel Hill Creek Basin in Pennsylvania, which provides recreational opportunities and drinking-water supply to an expanding population in southwestern Pennsylvania. The designation of the basin as a Critical Water Planning Area by the State and a Regional Water Resources Committee resulted in focused efforts to assess water quality and quantity in the basin to reduce the potential for further decline in the viability of the basin as an aquatic resource for humans and wildlife.

The water-quality assessment conducted for this study in 2007 showed that high chloride (Cl) concentrations (near or exceeding the 250 milligrams per liter (mg/L) drinking-water threshold) in Clear Run could be attributed to road deicing salts from the Pennsylvania Turnpike (Interstate 76). Immediately downstream from the confluence with Clear Run, Cl concentrations in the main stem of Laurel Hill Creek were more than 100 mg/L. The Cl concentrations decreased with distance downstream because of dilution by tributaries and groundwater discharge to the main-stem channel. A secondary water-quality issue was elevated nutrient concentrations compared to regional criteria proposed by the U.S. Environmental Protection Agency to minimize eutrophication. All samples from the main stem of Laurel Hill Creek had total nitrogen (N) concentrations greater than the 0.31 mg/L criterion for streams in the Central and Eastern Forested Uplands (Ecoregion XI), and those samples from the upper part of the basin also had total phosphorus concentrations greater than or equal to the 0.01 mg/L criterion for streams. Measured total N concentrations in the upper part of the main stem of Laurel Hill Creek were as high as 1.42 mg/L, most likely caused by agricultural activities. Tributary subbasins (Kooser Run, 3.45 mg/L of total N and Lost Creek, 2.07 mg/L of total N in June 2007), which receive wastewater discharges, also had elevated total N concentrations. Analyses of samples collected from tributaries draining forested subbasins indicate that the bedrock provides limited buffering of acidic precipitation. For example, several samples collected from tributaries (Cole Run, Buck Run, Cranberry Glade Run, and Moore Run) underlain by the Allegheny or Pottsville Formations along the western ridge of the basin had pH values less than 6.0 and specific conductance less than 50 microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25°C). Manganese (Mn) was the only water-quality constituent in surface water that exceeded the U.S. Environmental Protection Agency maximum contaminant level or secondary maximum contaminant level (SMCL). Mn concentrations exceeded the SMCL of 50 micrograms per liter (µg/L) in 56 percent of the surface-water samples collected.

Stream-temperature probe data for 2007–10 indicate that the main stem of Laurel Hill Creek did not meet the criteria for a cold-water fishery (CWF) during summer months. The maximum temperature for a cold-water fishery varies from

15.5 degrees Celsius (°C) for June 1–15 to 18.9 °C for July 1 through August 31. The average maximum stream temperatures for June through August at the five sites instrumented with temperature probes exceeded the maximum temperature criteria for a CWF. The average maximum temperatures in June at the five instrumented sites ranged from 19.2 °C to 22.0 °C, in July from 20.7 °C to 25.5 °C, and in August from 20.7 °C to 26.0 °C.

Groundwater samples collected in 2007 showed that geology is an important factor in water quality. Groundwater samples collected in areas underlain by the Mauch Chunk Formation had the highest pH and alkalinity values; in contrast, groundwater samples collected in wells underlain by the Allegheny and Pottsville Formations had the lowest pH and alkalinity values. Fifty-two percent of the samples collected from wells exceeded the SMCL for iron (Fe) and Mn. The Allegheny and Pottsville Formations had the highest Fe and Mn concentrations, respectively. Water samples from springs generally had lower concentrations of dissolved ions than the samples from wells.

Measured streamflows during base-flow periods indicate that tributaries draining the western, mostly forested part of the basin yield more water than other tributaries. Water withdrawals for public or private water supplies were not readily evident from measured streamflows. The main stem of Laurel Hill Creek yielded an average flow per unit area of 0.16 cubic feet per second per square mile ($ft^3/s/mi^2$). The average streamflows measured during 2007 at the upper site (03079320) was 0.28 cubic foot per second (0.18 Mgal/d) and at the lower site (03080000) was 18 cubic foot per second (11.6 Mgal/d). Even though water withdrawals were not readily apparent in measured streamflows, criteria established by the Pennsylvania Department of Environmental Protection (PaDEP) and tested with the Water-Analysis Screening Tool (WAST) indicate that the “safe yield” of water withdrawals from the basin was exceeded by 0.46 million gallons per day (Mgal/d). This is about 32 percent greater than the safe yield for the entire basin. Withdrawals are mainly concentrated in the upper one-half of the basin, and three subbasins have safe yields that were greatly exceeded (withdrawals were more than 500 percent of the safe yield).

A groundwater and surface-water flow model (GSFLOW) was developed for the Laurel Hill Creek Basin as a tool that could be used in the future as water use changes in the basin. The development of a single-layer GSFLOW model had some limitations due to the complexity of the groundwater-flow system of the study area, which is an area of high relief underlain by layered sedimentary rocks that impart a high ratio of horizontal to vertical anisotropy with respect to hydraulic conductivity. In the upland areas, the large vertical hydraulic gradients necessary for downward movement of groundwater could not be simulated with a one-layer model, whereas a multi-layer model would provide the ability to adjust hydraulic conductivities for different layers of the system. Another limitation of the GSFLOW model is the computational time step of one day. This problem primarily affects simulated flow near the land surface which generally changes at a faster time step than subsurface flows. Consequently, the daily time step may result in errors due to time averaging for simulated components of the system, such as surface runoff, infiltration, interflow, streamflow, and streambed leakage. For this reason, it was deemed more critical that the simulated water balance be representative of the observed water balance as opposed to simulating storm hydrographs that match observed hydrographs.

The GSFLOW model for the Laurel Hill Creek Basin was calibrated using streamflow data collected for Laurel Hill Creek at Ursina, Pa., from 1991 to 2007. Net water withdrawals decreased from 2.01 to 1.93 Mgal/d from 2003 to 2009 with surface-water withdrawals decreasing by 0.14 Mgal/d. Since 2009, water from a nearby reservoir outside the basin has been accessible to water suppliers in the basin to augment water supply that was previously withdrawn from the Laurel Hill Creek Basin. Such a change in water use could be input to the GSFLOW model developed for the basin if that information is needed. Results of the GSFLOW model for the basin developed for 1991–2007 indicate that most of the streamflow in Laurel Hill Creek was derived primarily from subsurface flow or interflow and secondarily from groundwater sources. The vast majority of interflow to the stream was through gradual water movement as opposed to fast flow through macropores. Surface runoff from the GSFLOW model was estimated to account for only 13 percent of the total streamflow from 1991 to 2007. Changes to land use would affect the proportion of streamflow derived from these various sources, and the parameterization of physical attributes in the GSFLOW model can be adjusted for particular Hydrologic Response Units to account for any changes to land use.

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Table 9. Description of parameters used in the coupled GSFLOW model for the Laurel Hill Creek Basin, southwestern, Pennsylvania, and modules that invoke that particular parameter.

[HRU, Hydrologic Response Unit; ft^3/s, cubic feet per second; m^3/s, cubic meters per second]

Parameter	Module	Description
adjmix_rain	precip_dist2	Monthly factor to adjust rain proportion in a mixed rain/snow event.
albset_rna	snowcomp	Decimal fraction of rain in a mixed rain and snow event above which snow albedo is not reset. (Applied when snowpack is accumulating)
albset_rnm	snowcomp	Decimal fraction of rain in a mixed rain and snow event above which snow albedo is not reset. (Applied when snowpack is melting)
albset_sna	snowcomp	Minimum snow fall, in water equivalent, needed to reset snow albedo when snowpack is accumulating as a decimal fraction.
albset_snm	snowcomp	Minimum snow fall, in water equivalent, needed to reset snow albedo when snowpack is melting as a decimal fraction.
basin_area	basin	Total area of watershed.
basin_solsta	ddsolrad_hru	Identifier of measurement station used in computing solar radiation.
basin_tsta	temp_dist2	Identifier of the measurement station used to compute basin air temperature.
carea_max	srunoff_smidx_casc	Maximum possible area contributing to surface runoff expressed as a portion of the HRU area.
cascade_flg	cascade	Type of cascade routing. (0=allow many-to-many; 1=only allow one-to-one)
cascade_tol	cascade	Minimum area of upslope HRU for computing cascading flow; cascade area below which a cascade link is ignored.
cecn_coef	snowcomp	Monthly convection-condensation energy coefficient.
circle_switch	cascade	Switch to check for circles. (0=no check; 1=check)
cov_type	intcp, snowcomp, soilzone	Vegetation cover type for each HRU. (0=bare soil; 1=grasses; 2=shrubs; 3=trees)
covden_sum	intcp, snowcomp, soilzone	Summer plant canopy density as a decimal fraction of the HRU area.
covden_win	intcp, snowcomp, soilzone	Winter plant canopy density as a decimal fraction of the HRU area.
dday_intcp	ddsolrad_hru	Intercept of monthly degree-day to temperature relation.
dday_slope	ddsolrad_hru	Slope of monthly degree-day to temperature relation.
den_init	snowcomp	Density of new-fallen snow as a decimal fraction.
den_max	snowcomp	Average maximum snowpack density as a decimal fraction of the liquid water equivalent.
dist_max	temp_dist2	Maximum distance from HRU to include a climate station.
elev_units	basin	Units of elevation. (0=feet; 1=meters)
emis_noppt	snowcomp	Emissivity of air on days without precipitation.
epan_coef	intcp	Monthly evaporation pan coefficient.
fastcoef_lin	soilzone	Linear flow-routing coefficient for fast interflow.
fastcoef_sq	soilzone	Non-linear flow-routing coefficient for fast interflow.
freeh2o_cap	snowcomp	Free-water holding capacity of snowpack expressed as decimal fraction of total snowpack water equivalent.
gvr_cell_id	gsflow_setconv, gsflow_prms2mf, gsflow_mf2prms, gsflow_budget	MODFLOW (finite-difference) cell associated with a gravity reservoir.
gvr_cell_pct	gsflow_setconv, gsflow_prms2mf	Proportion of the MODFLOW (finite-difference) cell area associated with each gravity reservoir.
gvr_hru_id	soilzone, gsflow_prms2mf, gsflow_mf2prms, gsflow_budget	Identifier of HRU corresponding to each gravity reservoir.

Table 9. Description of parameters used in the coupled GSFLOW model for the Laurel Hill Creek Basin, southwestern, Pennsylvania, and modules that invoke that particular parameter.—Continued

[HRU, Hydrologic Response Unit; ft^3/s, cubic feet per second; m^3/s, cubic meters per second]

Parameter	Module	Description
gvr_hru_pct	soilzone, gsflow_prms2mf, gsflow_mf2prms, gsflow_budget	Decimal fraction of HRU area associated with gravity reservoir.
hru_area	basin, cascade, temp_dist2, ddsolrad_hru, potet_jh, snowcomp, srunoff_smidx_casc, gsflow_prms2mf, gsflow_mf2prms, gsflow_budget	Area of HRU.
hru_aspect	soltab_hru	Aspect of HRU.
hru_deplcrv	snowcomp	Identifier of snowpack areal-depletion curve for HRU.
hru_down_id	cascade	Identifier of HRU that receives flow for each cascade link; if hru_strmseg_down_id is not 0 for a cascade link, hru_down_id is ignored.
hru_elev	basin, temp_dist2	Mean land-surface elevation of HRU.
hru_lat	soltab_hru	Latitude of HRU centroid.
hru_pct_up	cascade	Decimal fraction of area in the upslope HRU that contributes Hortonian runoff to the downslope HRU or to a stream segment.
hru_percent_imperv	basin, srunoff_smidx_casc	Decimal fraction of HRU area that is impervious.
hru_slope	basin, soltab_hru	Slope of HRU, specified as change in vertical length divided by change in horizontal length.
hru_solsta	soltab_hru	Index of solar radiation station associated with each HRU.
hru_strmseg_down_id	cascade	Identifier of stream segment that receives flow for each cascade link.
hru_type	basin, cascade, intcp, snowcomp, srunoff_smidx_casc, gsflow_prms2mf, gsflow_mf2prms, gsflow_budget	Type of each HRU. (0=inactive; 1=land; 2=lake; 3=swale)
hru_up_id	cascade	Identifier of HRU that contributes flow for each cascade link.
hru_xlong	temp_dist2, precip_dist2	Longitude of HRU centroid, state plane coordinates.
hru_ylat	temp_dist2, precip_dist2	Latitude of HRU centroid, state plane coordinates.
id_obsrunoff	gsflow_sum	Identifier for streamflow-gaging station at outlet.
imperv_stor_max	srunoff_smidx_casc	Maximum impervious area retention storage for each HRU.
jh_coef	potet_jh	Monthly air temperature coefficient used in Jensen-Haise potential evapotranspiration equation.
jh_coef_hru	potet_jh	Air temperature coefficient used in Jensen-Haise (Jensen and others, 1969) potential evapotranspiration equation for each HRU.
lapsemax_max	temp_dist2	Monthly maximum lapse rate from historical data used to constrain highest daily maximum lapse rate.
lapsemax_min	temp_dist2	Monthly minimum lapse rate from historical data used to constrain lowest daily maximum lapse rate.
lapsemin_max	temp_dist2	Monthly maximum lapse rate from historical data used to constrain highest daily minimum lapse rate.
lapsemin_min	temp_dist2	Monthly minimum lapse rate from historical data used to constrain lowest daily minimum lapse rate.
max_psta	precip_dist2	Maximum number of precipitation stations to distribute to an HRU.

Table 9. Description of parameters used in the coupled GSFLOW model for the Laurel Hill Creek Basin, southwestern, Pennsylvania, and modules that invoke that particular parameter.—Continued

[HRU, Hydrologic Response Unit; ft^3/s, cubic feet per second; m^3/s, cubic meters per second]

Parameter	Module	Description
max_tsta	temp_dist2	Maximum number of temperature stations to distribute to an HRU.
maxday_prec	precip_dist2	Maximum measured precipitation value above which precipitation is assumed to be in error.
melt_force	snowcomp	Julian date to force snowmelt.
melt_look	snowcomp	Julian date to start looking for beginning of snowmelt.
mnsziter	gsflow_prms2mf	Minimum number of iterations soil-zone states are computed.
monmax	temp_dist2	Monthly maximum air temperature from historical data used to constrain lowest daily maximum air temperatures.
monmin	temp_dist2	Monthly minimum air temperature from historical data used to constrain lowest daily minimum air temperatures.
mxsziter	gsflow_prms2mf	Maximum iterations for computing soil-zone flow to finite-difference cells during a time step.
potet_sublim	intcp, snowcomp	Fraction of potential evapotranspiration sublimated from snow surface as a decimal fraction.
ppt_rad_adj	ddsolrad_hru	Precipitation threshold used to determine if solar radiation is adjusted for cloud cover; if basin precipitation exceeds this value, radiation is mutiplied by radj_sppt or radj_wppt adjustment factor.
precip_units	precip_dist2	Units for measured precipitation. (0=inches; 1=millimeters)
pref_flow_den	soilzone	Decimal fraction of the soil zone available for preferential flow.
psta_mon	precip_dist2	Mean monthly precipitation at each measurement station.
psta_xlong	precip_dist2	Longitude of each measurement station that measures precipitation.
psta_ylat	precip_dist2	Latitude of each measurement station that measures precipitation.
rad_conv	ddsolrad_hru	Factor to convert measured solar radiation to langleys.
rad_trncf	snowcomp	Transmission coefficient for short-wave radiation through winter plant canopy on an HRU as a decimal fraction.
radadj_intcp	ddsolrad_hru	Intercept of solar radiation adjustment to temperature.
radadj_slope	ddsolrad_hru	Slope of solar radiation adjustment to temperature.
radj_sppt	ddsolrad_hru	Precipitation-day adjustment factor to solar radiation for a summer day with precipitation greater than ppt_rad_adj as a decimal fraction.
radj_wppt	ddsolrad_hru	Precipitation-day adjustment factor to solar radiation for a winter day with precipitation greater than ppt_rad_adj as a decimal fraction.
radmax	ddsolrad_hru	Maximum fraction of potential solar radiation that reaches land surface as a decimal fraction.
rain_mon	precip_dist2	Monthly rain factor on each HRU to adjust precipitation distributed to each HRU to account for differences in elevation.
runoff_units	gsflow_sum	Measured runoff units. (0=ft^3/s; 1=m^3/s)
sat_threshold	soilzone	Water holding capacity of the gravity and preferential-flow reservoirs; difference between field capacity and total soil saturation for each HRU.
settle_const	snowcomp	Snowpack settlement-time constant.
slowcoef_lin	soilzone	Linear flow-routing coefficient for slow interflow.
slowcoef_sq	soilzone	Non-linear flow-routing coefficient for slow interflow.
smidx_coef	srunoff_smidx_casc	Coefficient in non-linear contributing area algorithm.

Table 9. Description of parameters used in the coupled GSFLOW model for the Laurel Hill Creek Basin, southwestern, Pennsylvania, and modules that invoke that particular parameter.—Continued

[HRU, Hydrologic Response Unit; ft^3/s, cubic feet per second; m^3/s, cubic meters per second]

Parameter	Module	Description
smidx_exp	srunoff_smidx_casc	Exponent in non-linear contributing area algorithm.
snarea_curve	snowcomp	Snow area-depletion curve values, 11 for each curve as a decimal fraction.
snarea_thresh	snowcomp	Maximum threshold snowpack water equivalent below which the snow-covered-area curve is applied.
snow_intcp	intcp	Snow interception storage capacity for the major vegetation type in each HRU.
snow_mon	precip_dist2	Monthly snow factor on each HRU to adjust precipitation distributed to each HRU to account for differences in elevation.
snowinfil_max	srunoff_smidx_casc	Daily maximum snowmelt infiltration for the HRU.
soil_moist_init	soilzone	Initial value of available water in capillary reservoir.
soil_moist_max	soilzone	Maximum available water holding capacity of capillary reservoir from land surface to rooting depth of the major vegetation type of each HRU.
soil_rechr_init	soilzone	Initial storage for soil recharge zone (upper part of capillary reservoir where losses occur as evaporation and transpiration) for each HRU.
soil_rechr_max	soilzone	Maximum storage for soil recharge zone. (upper portion of capillary reservoir where losses occur as evaporation and transpiration)
soil_type	soilzone	Soil type in HRU. (1=sand; 2=loam; 3=clay)
soil2gw_max	soilzone	Maximum amount of the capillary reservoir excess that is routed directly to the groundwater reservoir for each HRU.
srain_intcp	intcp	Summer rain interception storage capacity for the major vegetation type in each HRU.
ssr2gw_exp	soilzone	Non-linear coefficient in equation used to route water from the gravity reservoir to the groundwater reservoir for each HRU.
ssr2gw_rate	soilzone	Linear coefficient in equation used to route water from the gravity reservoir to the groundwater reservoir for each HRU.
ssstor_init	soilzone	Initial storage of the gravity and preferential-flow reservoirs for each HRU.
szconverge	gsflow_prms2mf	Convergence criterion for checking soil-zone flows.
temp_units	temp_dist2, precip_dist2, potet_jh	Units of air temperature. (0=degrees Fahrenheit; 1=degrees Celsius)
tmax_allrain	precip_dist2, ddsolrad_hru	Monthly minimum air temperature at an HRU that results in all precipitation during a day being rain; if HRU air temperature is greater than or equal to this value, precipitation is rain.
tmax_allsnow	precip_dist2, snowcomp	Monthly maximum air temperature at which precipitation is all snow for the HRU; if HRU air temperature is less than or equal to this value, precipitation is snow.
tmax_index	ddsolrad_hru	Maximum monthly air temperature used to adjust solar radiation for precipitation.
tmax_mo_adj	temp_dist2	Monthly (January to December) adjustment factor to maximum air temperature for each HRU, estimated on the basis of slope and aspect.
tmin_mo_adj	temp_dist2	Monthly (January to December) adjustment factor to minimum air temperature for each HRU, estimated on the basis of slope and aspect.
transp_beg	potet_jh	Beginning month for transpiration computations at HRU.
transp_end	potet_jh	Ending month for transpiration computations at HRU.
transp_tmax	potet_jh	Maximum temperature used to determine when transpiration begins in each HRU.
tsta_elev	temp_dist2	Elevation of the air temperature measurement stations.

Table 9. Description of parameters used in the coupled GSFLOW model for the Laurel Hill Creek Basin, southwestern, Pennsylvania, and modules that invoke that particular parameter.—Continued

[HRU, Hydrologic Response Unit; ft^3/s, cubic feet per second; m^3/s, cubic meters per second]

Parameter	Module	Description
tsta_xlong	temp_dist2	Longitude of measurement stations that measure air temperature.
tsta_ylat	temp_dist2	Latitude of measurement stations that measure air temperature.
tstorm_mo	snowcomp	Monthly storm prevalence. (0=frontal storms prevalent; 1=convective storms prevalent)
wrain_intcp	intcp	Winter rain interception storage capacity for the major vegetation type in the HRU.

Appendixes 1, 2, 3, and 4

Appendix 1

Concentrations of selected water-quality constituents and values of selected physical characteristics in surface-water samples collected during low-flow conditions in the Laurel Hill Creek Basin, southwestern, Pennsylvania, June and September 2007. (Appendix 1 available online as Excel file at https://doi.org/10.3133/sir20165082)

Appendix 2

Monthly maximum stream temperature criteria established by the Commonwealth of Pennsylvania (2009), and monthly daily maximum, minimum, and mean stream temperatures for five sites along the main stem of Laurel Hill Creek Basin, southwestern, Pennsylvania, 2007–10.

Appendix 3

Daily mean streamflow values for station 03080000, Laurel Hill Creek at Ursina, Pennsylvania, July 17, 2007, through July 8, 2010.

Appendix 4

Concentrations of selected water-quality constituents and values of selected physical characteristics in groundwater samples collected in the Laurel Hill Creek Basin, southwestern, Pennsylvania, summer and fall 2007. (Appendix 4 available online as Excel file at https://doi.org/10.3133/sir20165082)

Table 2-1. Monthly maximum stream temperature criteria established by the Commonwealth of Pennsylvania (2009), and monthly daily maximum, minimum, and mean stream temperatures for five sites along the main stem of Laurel Hill Creek Basin, southwestern, Pennsylvania, 2007–2010.

[Temperature is in degrees Celsius; PA thermal maximum, maximum monthly stream temperature designated by the Commonwealth of Pennsylvania for a high-quality cold-water fishery; Min, average daily minimum stream temeprature in degrees Celsius; Mean, average stream temperature in degrees Celsius; Max, average daily maximum stream temperature in degrees Celsius; gray shading indicates missing data; data are available at the U.S. Geological Survey National Water Information System (NWIS) website (http://dx.doi.org/10.5066/F7P55KJN)]

Year	Month	PA thermal maximum	Station														
			03079420			03079550			03079660			03079748			03080100		
			Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
2007	7	18.9	18.8	20.0	21.8	19.5	20.3	21.1	20.6	21.6	22.7	19.9	21.3	23.0	19.8	22.9	26.9
2007	8	18.9	19.0	20.0	21.3	19.6	20.5	21.4	20.9	22.1	23.4	19.8	21.3	23.2	20.5	22.8	25.9
2007	9	17.8	15.7	17.0	18.3	17.0	17.8	18.7	18.4	19.7	21.0	17.4	18.8	20.5	17.3	20.5	25.5
2007	10	12.2	12.1	12.9	13.9	13.0	13.5	14.0	13.7	14.7	15.7	13.1	14.1	15.5	13.1	15.4	18.9
2007	11	7.8	4.8	5.7	6.6	5.6	6.2	6.8	5.7	6.3	6.9	5.2	6.0	7.0	4.8	6.1	7.6
2007	12	4.4	2.2	3.0	3.7	2.8	3.3	3.9	2.6	3.0	3.5	2.8	3.4	4.2	2.6	3.3	4.0
2008	1	3.3	1.2	1.6	2.1	1.5	1.8	2.3	1.4	1.7	2.1	1.3	1.7	2.2	1.1	1.6	2.1
2008	2	3.3	0.7	1.4	2.1	1.0	1.7	2.4	0.9	1.5	2.1	0.9	1.6	2.4	0.9	1.5	2.4
2008	3	5.6	2.6	3.8	5.3	3.3	4.2	5.2	3.5	4.1	5.0	3.1	4.2	5.8	3.2	4.5	5.9
2008	4	11.1	8.9	10.4	12.4	9.4	10.6	12.1	10.2	11.2	12.7	8.9	10.8	13.2	9.7	11.6	14.0
2008	5	14.4	10.6	12.3	14.2	11.2	12.4	13.8	11.9	12.9	14.1	10.8	12.5	14.7	11.5	13.2	15.1
2008	6	17.8	17.1	18.4	19.8	17.4	18.6	20.0	18.7	20.0	21.7	16.9	18.9	21.4	18.0	20.4	23.3
2008	7	18.9	18.6	19.9	21.3	18.9	20.1	21.4	20.9	22.3	24.0	18.8	20.9	23.4	19.7	22.4	25.9
2008	8	18.9	17.3	18.6	20.0	18.1	19.1	20.1	20.0	21.3	22.7	17.8	19.5	21.4	18.3	21.2	25.1
2008	9	17.8	15.3	16.4	17.5	16.6	17.5	18.4	17.9	18.8	19.8	16.5	17.6	19.1	16.6	19.2	23.0
2008	10	12.2	8.8	9.6	10.5	9.4	10.1	10.9	10.4	11.3	12.2	9.7	10.6	12.0	9.3	11.5	14.8
2008	11	7.8	4.1	4.7	5.5	4.4	5.0	5.7	4.3	5.0	5.7	4.4	5.1	6.0	3.8	5.1	6.5
2008	12	4.4	1.7	2.3	3.1	2.1	2.8	3.4	2.1	2.5	3.1	2.2	2.8	3.6	1.9	2.7	3.4
2009	1	3.3	0.3	0.5	0.7	0.4	0.6	0.9	0.4	0.6	0.7	0.4	0.7	1.0	0.1	0.5	0.8
2009	2	3.3	0.8	1.3	1.8	1.1	1.5	2.1	0.9	1.3	1.9	0.9	1.4	2.1	0.7	1.4	2.2
2009	3	5.6	4.0	5.1	6.5	4.5	5.5	6.7	4.7	5.7	7.0	4.0	5.3	7.2	4.1	5.9	8.2
2009	4	11.1	7.3	9.0	11.1	8.0	9.3	10.7	8.6	9.5	10.8	7.2	9.1	11.5	8.1	9.9	11.8
2009	5	14.4	12.2	13.8	15.5	12.6	13.9	15.5	14.0	15.0	16.5	12.0	13.8	16.1	13.3	15.4	17.8
2009	6	17.8	16.0	17.0	18.0	16.0	17.2	18.4	17.1	18.4	20.0	15.2	16.9	19.0	16.4	18.5	20.7
2009	7	18.9	17.4	18.3	19.4	17.3	18.5	19.7	18.9	20.4	22.1	17.6	19.5	21.7	18.3	21.2	24.5
2009	8	18.9	19.4	20.2	21.0	18.9	20.2	21.4	21.3	22.5	23.6	20.0	21.6	23.5	20.4	23.1	27.0
2009	9	17.8	15.6	16.3	17.1	14.0	15.7	17.1	17.5	18.4	19.4	16.3	17.4	18.9	16.3	18.9	22.3
2009	10	12.2	9.3	9.9	10.6	9.6	10.1	10.7	9.9	10.4	10.9	9.2	10.1	11.2	9.3	10.5	11.9

Table 2-1. Monthly maximum stream temperature criteria established by the Commonwealth of Pennsylvania (2009), and monthly daily maximum, minimum, and mean stream temperatures for five sites along the main stem of Laurel Hill Creek Basin, southwestern, Pennsylvania, 2007–2010.—Continued

[Temperature is in degrees Celsius; PA thermal maximum, maximum monthly stream temperature designated by the Commonwealth of Pennsylvania for a high-quality cold-water fishery; Min, average daily minimum stream temeprature in degrees Celsius; Mean, average stream temperature in degrees Celsius; Max, average daily maximum stream temperature in degrees Celsius; gray shading indicates missing data; Data are available at the U.S. Geological Survey National Water Information System (NWIS) website (http://dx.doi.org/10.5066/F7P55KJN)]

Year	Month	PA thermal maximum	Station														
			03079420			03079550			03079660			03079748			03080100		
			Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
2009	11	7.8	6.2	6.9	7.7	6.8	7.4	8.0	6.4	7.2	7.8	6.6	7.5	8.4	5.6	7.0	8.7
2009	12	4.4	1.1	1.6	2.2	1.5	1.9	2.4				1.5	2.2	2.9			
2010	1	3.3	0.4	0.7	0.9	0.6	0.8	1.1				1.0	1.3	1.7			
2010	2	3.3	0.0	0.1	0.1	0.1	0.2	0.4				0.6	0.7	0.9			
2010	3	5.6	2.3	3.4	4.8	2.9	3.7	4.7				3.8	4.5	5.7			
2010	4	11.1	8.9	10.8	13.1	9.5	11.0	13.0				8.8	11.4	14.5			
2010	5	14.4	12.0	13.7	15.4							12.0	13.7	16.0			
2010	6	17.8	17.9	19.1	20.4							17.9	20.0	22.5			
2010	7	18.9	18.5	20.4	22.3							19.2	22.1	25.4			

Table 3-1. Daily mean streamflow values for station 03080000, Laurel Hill Creek at Ursina, Pennsylvania, July 17, 2007, through July 8, 2010.

[Data are available at the U.S. Geological Survey National Water Information System (NWIS) website (http://dx.doi.org/10.5066/F7P55KJN)]

Date	Daily mean streamflow, cubic feet per second	Date	Daily mean streamflow, cubic feet per second	Date	Daily mean streamflow, cubic feet per second
7/17/2007	24	8/26/2007	184	10/5/2007	13
7/18/2007	16	8/27/2007	134	10/6/2007	13
7/19/2007	20	8/28/2007	99	10/7/2007	12
7/20/2007	71	8/29/2007	82	10/8/2007	12
7/21/2007	49	8/30/2007	69	10/9/2007	12
7/22/2007	29	8/31/2007	60	10/10/2007	14
7/23/2007	21	9/1/2007	49	10/11/2007	14
7/24/2007	16	9/2/2007	38	10/12/2007	20
7/25/2007	14	9/3/2007	33	10/13/2007	23
7/26/2007	14	9/4/2007	30	10/14/2007	19
7/27/2007	21	9/5/2007	28	10/15/2007	16
7/28/2007	21	9/6/2007	26	10/16/2007	15
7/29/2007	17	9/7/2007	23	10/17/2007	15
7/30/2007	13	9/8/2007	20	10/18/2007	16
7/31/2007	11	9/9/2007	19	10/19/2007	16
8/1/2007	9	9/10/2007	23	10/20/2007	18
8/2/2007	6	9/11/2007	60	10/21/2007	20
8/3/2007	4	9/12/2007	101	10/22/2007	18
8/4/2007	3	9/13/2007	48	10/23/2007	17
8/5/2007	5	9/14/2007	29	10/24/2007	39
8/6/2007	32	9/15/2007	26	10/25/2007	101
8/7/2007	67	9/16/2007	23	10/26/2007	73
8/8/2007	49	9/17/2007	20	10/27/2007	68
8/9/2007	82	9/18/2007	17	10/28/2007	69
8/10/2007	357	9/19/2007	15	10/29/2007	48
8/11/2007	178	9/20/2007	15	10/30/2007	35
8/12/2007	90	9/21/2007	13	10/31/2007	30
8/13/2007	59	9/22/2007	13	11/1/2007	29
8/14/2007	39	9/23/2007	13	11/2/2007	32
8/15/2007	30	9/24/2007	12	11/3/2007	36
8/16/2007	40	9/25/2007	11	11/4/2007	35
8/17/2007	60	9/26/2007	10	11/5/2007	35
8/18/2007	36	9/27/2007	58	11/6/2007	58
8/19/2007	26	9/28/2007	61	11/7/2007	66
8/20/2007	147	9/29/2007	31	11/8/2007	57
8/21/2007	1730	9/30/2007	22	11/9/2007	57
8/22/2007	1230	10/1/2007	18	11/10/2007	46
8/23/2007	657	10/2/2007	15	11/11/2007	33
8/24/2007	357	10/3/2007	13	11/12/2007	101
8/25/2007	240	10/4/2007	13	11/13/2007	158

Table 3-1. Daily mean streamflow values for station 03080000, Laurel Hill Creek at Ursina, Pennsylvania, July 17, 2007, through July 8, 2010.—Continued

[Data are available at the U.S. Geological Survey National Water Information System (NWIS) website (http://dx.doi.org/10.5066/F7P55KJN)]

Date	Daily mean streamflow, cubic feet per second	Date	Daily mean streamflow, cubic feet per second	Date	Daily mean streamflow, cubic feet per second
11/14/2007	217	12/25/2007	616	2/4/2008	394
11/15/2007	852	12/26/2007	436	2/5/2008	1770
11/16/2007	562	12/27/2007	359	2/6/2008	3220
11/17/2007	315	12/28/2007	326	2/7/2008	2330
11/18/2007	246	12/29/2007	541	2/8/2008	1100
11/19/2007	205	12/30/2007	469	2/9/2008	687
11/20/2007	183	12/31/2007	378	2/10/2008	531
11/21/2007	171	1/1/2008	335	2/11/2008	396
11/22/2007	151	1/2/2008	302	2/12/2008	345
11/23/2007	142	1/3/2008	271	2/13/2008	326
11/24/2007	119	1/4/2008	221	2/14/2008	276
11/25/2007	107	1/5/2008	239	2/15/2008	263
11/26/2007	169	1/6/2008	493	2/16/2008	196
11/27/2007	964	1/7/2008	663	2/17/2008	199
11/28/2007	572	1/8/2008	492	2/18/2008	473
11/29/2007	368	1/9/2008	415	2/19/2008	465
11/30/2007	279	1/10/2008	347	2/20/2008	345
12/1/2007	224	1/11/2008	997	2/21/2008	308
12/2/2007	241	1/12/2008	963	2/22/2008	287
12/3/2007	1260	1/13/2008	599	2/23/2008	294
12/4/2007	756	1/14/2008	474	2/24/2008	252
12/5/2007	468	1/15/2008	379	2/25/2008	245
12/6/2007	364	1/16/2008	315	2/26/2008	265
12/7/2007	333	1/17/2008	276	2/27/2008	436
12/8/2007	308	1/18/2008	261	2/28/2008	332
12/9/2007	1060	1/19/2008	230	2/29/2008	283
12/10/2007	2370	1/20/2008	196	3/1/2008	286
12/11/2007	1400	1/21/2008	136	3/2/2008	265
12/12/2007	889	1/22/2008	205	3/3/2008	270
12/13/2007	2180	1/23/2008	231	3/4/2008	878
12/14/2007	2330	1/24/2008	226	3/5/2008	2540
12/15/2007	1050	1/25/2008	185	3/6/2008	1260
12/16/2007	875	1/26/2008	221	3/7/2008	832
12/17/2007	614	1/27/2008	171	3/8/2008	911
12/18/2007	428	1/28/2008	161	3/9/2008	751
12/19/2007	351	1/29/2008	176	3/10/2008	539
12/20/2007	298	1/30/2008	1180	3/11/2008	484
12/21/2007	260	1/31/2008	831	3/12/2008	442
12/22/2007	231	2/1/2008	529	3/13/2008	384
12/23/2007	645	2/2/2008	507	3/14/2008	406
12/24/2007	1200	2/3/2008	386	3/15/2008	658

Table 3-1. Daily mean streamflow values for station 03080000, Laurel Hill Creek at Ursina, Pennsylvania, July 17, 2007, through July 8, 2010.—Continued

[Data are available at the U.S. Geological Survey National Water Information System (NWIS) website (http://dx.doi.org/10.5066/F7P55KJN)]

Date	Daily mean streamflow, cubic feet per second	Date	Daily mean streamflow, cubic feet per second	Date	Daily mean streamflow, cubic feet per second
3/16/2008	536	4/26/2008	223	6/6/2008	305
3/17/2008	409	4/27/2008	230	6/7/2008	227
3/18/2008	416	4/28/2008	385	6/8/2008	188
3/19/2008	792	4/29/2008	468	6/9/2008	151
3/20/2008	1030	4/30/2008	352	6/10/2008	131
3/21/2008	729	5/1/2008	309	6/11/2008	169
3/22/2008	554	5/2/2008	274	6/12/2008	116
3/23/2008	443	5/3/2008	249	6/13/2008	97
3/24/2008	362	5/4/2008	248	6/14/2008	117
3/25/2008	304	5/5/2008	201	6/15/2008	252
3/26/2008	258	5/6/2008	176	6/16/2008	143
3/27/2008	244	5/7/2008	153	6/17/2008	116
3/28/2008	290	5/8/2008	190	6/18/2008	101
3/29/2008	267	5/9/2008	420	6/19/2008	125
3/30/2008	227	5/10/2008	1610	6/20/2008	93
3/31/2008	218	5/11/2008	1280	6/21/2008	82
4/1/2008	217	5/12/2008	1270	6/22/2008	85
4/2/2008	206	5/13/2008	904	6/23/2008	74
4/3/2008	179	5/14/2008	606	6/24/2008	66
4/4/2008	191	5/15/2008	556	6/25/2008	55
4/5/2008	310	5/16/2008	925	6/26/2008	49
4/6/2008	267	5/17/2008	942	6/27/2008	73
4/7/2008	236	5/18/2008	1460	6/28/2008	72
4/8/2008	216	5/19/2008	1250	6/29/2008	66
4/9/2008	206	5/20/2008	956	6/30/2008	108
4/10/2008	191	5/21/2008	870	7/1/2008	113
4/11/2008	181	5/22/2008	650	7/2/2008	92
4/12/2008	258	5/23/2008	475	7/3/2008	74
4/13/2008	235	5/24/2008	373	7/4/2008	131
4/14/2008	230	5/25/2008	306	7/5/2008	168
4/15/2008	206	5/26/2008	253	7/6/2008	117
4/16/2008	191	5/27/2008	229	7/7/2008	101
4/17/2008	182	5/28/2008	245	7/8/2008	101
4/18/2008	170	5/29/2008	182	7/9/2008	101
4/19/2008	156	5/30/2008	147	7/10/2008	137
4/20/2008	400	5/31/2008	320	7/11/2008	98
4/21/2008	472	6/1/2008	339	7/12/2008	81
4/22/2008	368	6/2/2008	214	7/13/2008	69
4/23/2008	318	6/3/2008	175	7/14/2008	64
4/24/2008	278	6/4/2008	205	7/15/2008	49
4/25/2008	245	6/5/2008	410	7/16/2008	42

Table 3-1 Daily mean streamflow values for station 03080000, Laurel Hill Creek at Ursina, Pennsylvania, July 17, 2007, through July 8, 2010.—Continued

[Data are available at the U.S. Geological Survey National Water Information System (NWIS) website (http://dx.doi.org/10.5066/F7P55KJN)]

Date	Daily mean streamflow, cubic feet per second	Date	Daily mean streamflow, cubic feet per second	Date	Daily mean streamflow, cubic feet per second
7/17/2008	38	8/27/2008	12	10/7/2008	16
7/18/2008	33	8/28/2008	31	10/8/2008	15
7/19/2008	30	8/29/2008	72	10/9/2008	17
7/20/2008	27	8/30/2008	45	10/10/2008	20
7/21/2008	33	8/31/2008	36	10/11/2008	18
7/22/2008	107	9/1/2008	23	10/12/2008	15
7/23/2008	508	9/2/2008	18	10/13/2008	12
7/24/2008	373	9/3/2008	14	10/14/2008	11
7/25/2008	179	9/4/2008	11	10/15/2008	12
7/26/2008	114	9/5/2008	10	10/16/2008	13
7/27/2008	94	9/6/2008	14	10/17/2008	15
7/28/2008	77	9/7/2008	14	10/18/2008	16
7/29/2008	61	9/8/2008	13	10/19/2008	16
7/30/2008	56	9/9/2008	332	10/20/2008	16
7/31/2008	272	9/10/2008	198	10/21/2008	15
8/1/2008	192	9/11/2008	83	10/22/2008	16
8/2/2008	480	9/12/2008	80	10/23/2008	17
8/3/2008	289	9/13/2008	275	10/24/2008	16
8/4/2008	184	9/14/2008	176	10/25/2008	23
8/5/2008	130	9/15/2008	106	10/26/2008	52
8/6/2008	130	9/16/2008	91	10/27/2008	41
8/7/2008	100	9/17/2008	67	10/28/2008	33
8/8/2008	83	9/18/2008	47	10/29/2008	38
8/9/2008	72	9/19/2008	39	10/30/2008	44
8/10/2008	58	9/20/2008	35	10/31/2008	41
8/11/2008	51	9/21/2008	32	11/1/2008	41
8/12/2008	46	9/22/2008	29	11/2/2008	42
8/13/2008	41	9/23/2008	26	11/3/2008	37
8/14/2008	37	9/24/2008	23	11/4/2008	33
8/15/2008	34	9/25/2008	23	11/5/2008	35
8/16/2008	32	9/26/2008	21	11/6/2008	42
8/17/2008	27	9/27/2008	25	11/7/2008	42
8/18/2008	26	9/28/2008	34	11/8/2008	41
8/19/2008	24	9/29/2008	31	11/9/2008	41
8/20/2008	20	9/30/2008	26	11/10/2008	41
8/21/2008	18	10/1/2008	23	11/11/2008	39
8/22/2008	16	10/2/2008	21	11/12/2008	39
8/23/2008	15	10/3/2008	22	11/13/2008	48
8/24/2008	14	10/4/2008	21	11/14/2008	61
8/25/2008	13	10/5/2008	19	11/15/2008	60
8/26/2008	12	10/6/2008	18	11/16/2008	90

Table 3-1 Daily mean streamflow values for station 03080000, Laurel Hill Creek at Ursina, Pennsylvania, July 17, 2007, through July 8, 2010.—Continued

[Data are available at the U.S. Geological Survey National Water Information System (NWIS) website (http://dx.doi.org/10.5066/F7P55KJN)]

Date	Daily mean streamflow, cubic feet per second	Date	Daily mean streamflow, cubic feet per second	Date	Daily mean streamflow, cubic feet per second
11/17/2008	77	12/28/2008	1130	2/7/2009	257
11/18/2008	78	12/29/2008	673	2/8/2009	1850
11/19/2008	78	12/30/2008	474	2/9/2009	1690
11/20/2008	78	12/31/2008	382	2/10/2009	1320
11/21/2008	81	1/1/2009	325	2/11/2009	2390
11/22/2008	109	1/2/2009	296	2/12/2009	2140
11/23/2008	162	1/3/2009	233	2/13/2009	1170
11/24/2008	161	1/4/2009	223	2/14/2009	664
11/25/2008	428	1/5/2009	352	2/15/2009	468
11/26/2008	343	1/6/2009	326	2/16/2009	365
11/27/2008	235	1/7/2009	1010	2/17/2009	307
11/28/2008	201	1/8/2009	1260	2/18/2009	286
11/29/2008	176	1/9/2009	627	2/19/2009	390
11/30/2008	182	1/10/2009	456	2/20/2009	331
12/1/2008	375	1/11/2009	471	2/21/2009	312
12/2/2008	303	1/12/2009	374	2/22/2009	253
12/3/2008	230	1/13/2009	319	2/23/2009	229
12/4/2008	236	1/14/2009	285	2/24/2009	217
12/5/2008	313	1/15/2009	240	2/25/2009	215
12/6/2008	263	1/16/2009	183	2/26/2009	199
12/7/2008	224	1/17/2009	149	2/27/2009	237
12/8/2008	195	1/18/2009	206	2/28/2009	358
12/9/2008	177	1/19/2009	213	3/1/2009	297
12/10/2008	741	1/20/2009	226	3/2/2009	256
12/11/2008	1270	1/21/2009	190	3/3/2009	234
12/12/2008	1870	1/22/2009	190	3/4/2009	225
12/13/2008	916	1/23/2009	278	3/5/2009	232
12/14/2008	548	1/24/2009	190	3/6/2009	184
12/15/2008	471	1/25/2009	345	3/7/2009	185
12/16/2008	785	1/26/2009	309	3/8/2009	184
12/17/2008	1120	1/27/2009	249	3/9/2009	184
12/18/2008	1090	1/28/2009	292	3/10/2009	154
12/19/2008	2600	1/29/2009	528	3/11/2009	134
12/20/2008	3350	1/30/2009	326	3/12/2009	125
12/21/2008	1300	1/31/2009	286	3/13/2009	111
12/22/2008	660	2/1/2009	304	3/14/2009	105
12/23/2008	458	2/2/2009	251	3/15/2009	101
12/24/2008	1340	2/3/2009	244	3/16/2009	98
12/25/2008	2840	2/4/2009	258	3/17/2009	109
12/26/2008	1300	2/5/2009	200	3/18/2009	103
12/27/2008	1860	2/6/2009	312	3/19/2009	97

Table 3-1 Daily mean streamflow values for station 03080000, Laurel Hill Creek at Ursina, Pennsylvania, July 17, 2007, through July 8, 2010.—Continued

[Data are available at the U.S. Geological Survey National Water Information System (NWIS) website (http://dx.doi.org/10.5066/F7P55KJN)]

Date	Daily mean streamflow, cubic feet per second	Date	Daily mean streamflow, cubic feet per second	Date	Daily mean streamflow, cubic feet per second
3/20/2009	92	4/30/2009	206	6/10/2009	125
3/21/2009	83	5/1/2009	323	6/11/2009	109
3/22/2009	80	5/2/2009	1110	6/12/2009	157
3/23/2009	77	5/3/2009	769	6/13/2009	122
3/24/2009	71	5/4/2009	2290	6/14/2009	93
3/25/2009	68	5/5/2009	2010	6/15/2009	79
3/26/2009	181	5/6/2009	1100	6/16/2009	68
3/27/2009	424	5/7/2009	1390	6/17/2009	89
3/28/2009	335	5/8/2009	856	6/18/2009	2340
3/29/2009	329	5/9/2009	587	6/19/2009	751
3/30/2009	327	5/10/2009	425	6/20/2009	515
3/31/2009	284	5/11/2009	360	6/21/2009	1000
4/1/2009	268	5/12/2009	386	6/22/2009	787
4/2/2009	259	5/13/2009	297	6/23/2009	380
4/3/2009	378	5/14/2009	254	6/24/2009	260
4/4/2009	770	5/15/2009	225	6/25/2009	201
4/5/2009	472	5/16/2009	199	6/26/2009	163
4/6/2009	400	5/17/2009	212	6/27/2009	133
4/7/2009	365	5/18/2009	183	6/28/2009	107
4/8/2009	327	5/19/2009	150	6/29/2009	95
4/9/2009	326	5/20/2009	130	6/30/2009	91
4/10/2009	284	5/21/2009	112	7/1/2009	97
4/11/2009	323	5/22/2009	101	7/2/2009	189
4/12/2009	318	5/23/2009	91	7/3/2009	147
4/13/2009	273	5/24/2009	83	7/4/2009	123
4/14/2009	268	5/25/2009	94	7/5/2009	94
4/15/2009	301	5/26/2009	184	7/6/2009	76
4/16/2009	325	5/27/2009	172	7/7/2009	66
4/17/2009	276	5/28/2009	244	7/8/2009	57
4/18/2009	251	5/29/2009	246	7/9/2009	51
4/19/2009	233	5/30/2009	222	7/10/2009	45
4/20/2009	297	5/31/2009	165	7/11/2009	43
4/21/2009	486	6/1/2009	131	7/12/2009	44
4/22/2009	450	6/2/2009	159	7/13/2009	42
4/23/2009	502	6/3/2009	206	7/14/2009	37
4/24/2009	414	6/4/2009	201	7/15/2009	31
4/25/2009	359	6/5/2009	246	7/16/2009	28
4/26/2009	309	6/6/2009	218	7/17/2009	31
4/27/2009	266	6/7/2009	170	7/18/2009	38
4/28/2009	231	6/8/2009	135	7/19/2009	34
4/29/2009	223	6/9/2009	125	7/20/2009	28

Table 3-1 Daily mean streamflow values for station 03080000, Laurel Hill Creek at Ursina, Pennsylvania, July 17, 2007, through July 8, 2010.—Continued

[Data are available at the U.S. Geological Survey National Water Information System (NWIS) website (http://dx.doi.org/10.5066/F7P55KJN)]

Date	Daily mean streamflow, cubic feet per second	Date	Daily mean streamflow, cubic feet per second	Date	Daily mean streamflow, cubic feet per second
7/21/2009	49	8/31/2009	46	10/11/2009	539
7/22/2009	62	9/1/2009	34	10/12/2009	276
7/23/2009	57	9/2/2009	25	10/13/2009	195
7/24/2009	46	9/3/2009	21	10/14/2009	153
7/25/2009	36	9/4/2009	20	10/15/2009	194
7/26/2009	29	9/5/2009	18	10/16/2009	440
7/27/2009	26	9/6/2009	17	10/17/2009	334
7/28/2009	25	9/7/2009	16	10/18/2009	280
7/29/2009	32	9/8/2009	16	10/19/2009	240
7/30/2009	107	9/9/2009	16	10/20/2009	198
7/31/2009	100	9/10/2009	15	10/21/2009	163
8/1/2009	111	9/11/2009	14	10/22/2009	141
8/2/2009	82	9/12/2009	13	10/23/2009	130
8/3/2009	76	9/13/2009	13	10/24/2009	469
8/4/2009	55	9/14/2009	13	10/25/2009	446
8/5/2009	44	9/15/2009	12	10/26/2009	340
8/6/2009	41	9/16/2009	12	10/27/2009	321
8/7/2009	38	9/17/2009	11	10/28/2009	426
8/8/2009	31	9/18/2009	11	10/29/2009	381
8/9/2009	28	9/19/2009	10	10/30/2009	346
8/10/2009	26	9/20/2009	10	10/31/2009	316
8/11/2009	26	9/21/2009	10	11/1/2009	290
8/12/2009	37	9/22/2009	10	11/2/2009	252
8/13/2009	50	9/23/2009	10	11/3/2009	225
8/14/2009	38	9/24/2009	14	11/4/2009	202
8/15/2009	28	9/25/2009	14	11/5/2009	183
8/16/2009	23	9/26/2009	17	11/6/2009	160
8/17/2009	21	9/27/2009	68	11/7/2009	129
8/18/2009	21	9/28/2009	66	11/8/2009	119
8/19/2009	23	9/29/2009	45	11/9/2009	109
8/20/2009	21	9/30/2009	114	11/10/2009	76
8/21/2009	29	10/1/2009	112	11/11/2009	72
8/22/2009	36	10/2/2009	64	11/12/2009	66
8/23/2009	25	10/3/2009	61	11/13/2009	64
8/24/2009	20	10/4/2009	55	11/14/2009	62
8/25/2009	18	10/5/2009	40	11/15/2009	60
8/26/2009	16	10/6/2009	34	11/16/2009	58
8/27/2009	15	10/7/2009	32	11/17/2009	54
8/28/2009	14	10/8/2009	31	11/18/2009	52
8/29/2009	184	10/9/2009	237	11/19/2009	57
8/30/2009	93	10/10/2009	1210	11/20/2009	90

Table 3-1 Daily mean streamflow values for station 03080000, Laurel Hill Creek at Ursina, Pennsylvania, July 17, 2007, through July 8, 2010.—Continued

[Data are available at the U.S. Geological Survey National Water Information System (NWIS) website (http://dx.doi.org/10.5066/F7P55KJN)]

Date	Daily mean streamflow, cubic feet per second	Date	Daily mean streamflow, cubic feet per second	Date	Daily mean streamflow, cubic feet per second
11/21/2009	90	1/1/2010	211	2/11/2010	157
11/22/2009	77	1/2/2010	178	2/12/2010	154
11/23/2009	69	1/3/2010	158	2/13/2010	180
11/24/2009	68	1/4/2010	190	2/14/2010	132
11/25/2009	70	1/5/2010	194	2/15/2010	188
11/26/2009	67	1/6/2010	174	2/16/2010	227
11/27/2009	74	1/7/2010	192	2/17/2010	199
11/28/2009	83	1/8/2010	178	2/18/2010	171
11/29/2009	80	1/9/2010	181	2/19/2010	151
11/30/2009	149	1/10/2010	215	2/20/2010	188
12/1/2009	222	1/11/2010	273	2/21/2010	141
12/2/2009	187	1/12/2010	324	2/22/2010	119
12/3/2009	382	1/13/2010	304	2/23/2010	174
12/4/2009	354	1/14/2010	305	2/24/2010	172
12/5/2009	294	1/15/2010	234	2/25/2010	183
12/6/2009	252	1/16/2010	213	2/26/2010	130
12/7/2009	216	1/17/2010	535	2/27/2010	140
12/8/2009	197	1/18/2010	839	2/28/2010	140
12/9/2009	745	1/19/2010	652	3/1/2010	131
12/10/2009	911	1/20/2010	484	3/2/2010	122
12/11/2009	449	1/21/2010	384	3/3/2010	118
12/12/2009	403	1/22/2010	360	3/4/2010	166
12/13/2009	310	1/23/2010	335	3/5/2010	254
12/14/2009	599	1/24/2010	355	3/6/2010	249
12/15/2009	694	1/25/2010	4280	3/7/2010	255
12/16/2009	627	1/26/2010	2780	3/8/2010	263
12/17/2009	425	1/27/2010	1120	3/9/2010	294
12/18/2009	343	1/28/2010	676	3/10/2010	404
12/19/2009	318	1/29/2010	488	3/11/2010	894
12/20/2009	288	1/30/2010	400	3/12/2010	2710
12/21/2009	252	1/31/2010	335	3/13/2010	4100
12/22/2009	206	2/1/2010	305	3/14/2010	3740
12/23/2009	188	2/2/2010	251	3/15/2010	2180
12/24/2009	172	2/3/2010	214	3/16/2010	1810
12/25/2009	229	2/4/2010	192	3/17/2010	1730
12/26/2009	253	2/5/2010	174	3/18/2010	1510
12/27/2009	277	2/6/2010	182	3/19/2010	1360
12/28/2009	241	2/7/2010	274	3/20/2010	1400
12/29/2009	211	2/8/2010	218	3/21/2010	1370
12/30/2009	185	2/9/2010	209	3/22/2010	1430
12/31/2009	227	2/10/2010	163	3/23/2010	1800

Table 3-1. Daily mean streamflow values for station 03080000, Laurel Hill Creek at Ursina, Pennsylvania, July 17, 2007, through July 8, 2010.—Continued

[Data are available at the U.S. Geological Survey National Water Information System (NWIS) website (http://dx.doi.org/10.5066/F7P55KJN)]

Date	Daily mean streamflow, cubic feet per second
3/24/2010	1120
3/25/2010	783
3/26/2010	859
3/27/2010	619
3/28/2010	545
3/29/2010	736
3/30/2010	558
3/31/2010	453
4/1/2010	377
4/2/2010	325
4/3/2010	283
4/4/2010	247
4/5/2010	216
4/6/2010	197
4/7/2010	181
4/8/2010	164
4/9/2010	175
4/10/2010	137
4/11/2010	115
4/12/2010	106
4/13/2010	100
4/14/2010	100
4/15/2010	91
4/16/2010	94
4/17/2010	348
4/18/2010	236
4/19/2010	194
4/20/2010	168
4/21/2010	154
4/22/2010	138
4/23/2010	120
4/24/2010	108
4/25/2010	136
4/26/2010	389
4/27/2010	549
4/28/2010	390
4/29/2010	309
4/30/2010	258
5/1/2010	221
5/2/2010	222
5/3/2010	1160
5/4/2010	810
5/5/2010	489
5/6/2010	375
5/7/2010	289
5/8/2010	297
5/9/2010	287
5/10/2010	236
5/11/2010	262
5/12/2010	488
5/13/2010	386
5/14/2010	323
5/15/2010	319
5/16/2010	256
5/17/2010	407
5/18/2010	824
5/19/2010	560
5/20/2010	491
5/21/2010	382
5/22/2010	556
5/23/2010	1240
5/24/2010	687
5/25/2010	485
5/26/2010	371
5/27/2010	289
5/28/2010	232
5/29/2010	216
5/30/2010	166
5/31/2010	134
6/1/2010	137
6/2/2010	107
6/3/2010	90
6/4/2010	80
6/5/2010	95
6/6/2010	112
6/7/2010	84
6/8/2010	64
6/9/2010	139
6/10/2010	449
6/11/2010	221
6/12/2010	141
6/13/2010	122
6/14/2010	110
6/15/2010	122
6/16/2010	115
6/17/2010	90
6/18/2010	73
6/19/2010	62
6/20/2010	93
6/21/2010	71
6/22/2010	55
6/23/2010	51
6/24/2010	49
6/25/2010	59
6/26/2010	50
6/27/2010	41
6/28/2010	44
6/29/2010	39
6/30/2010	34
7/1/2010	29
7/2/2010	25
7/3/2010	24
7/4/2010	23
7/5/2010	22
7/6/2010	20
7/7/2010	20
7/8/2010	18

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