Hydrogeologic Setting and Ground-Water Flow in the Leetown Area, West Virginia

Scientific Investigations Report 2007–5066

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

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By Mark D. Kozar, David J. Weary, Katherine S. Paybins, and Herbert A. Pierce

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Suggested citation:
Kozar, M.D., Paybins, K.S., Weary, D.J., and Pierce, H.A., 2007, Hydrogeologic Setting and Ground-Water Flow in the Leetown Area, West Virginia: U.S. Geological Survey Scientific Investigations Report 2007-5066.

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Conversion Factors and Datum

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
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)
cubic foot per second per square mile [(ft^3/s)/mi^2]	0.01093	cubic meter per second per square kilometer [(m^3/s)/km^2]
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
gallons per day (gal/d)	0.003785	cubic meter per day (m^3/d)
	25.4	millimeter per year (mm/yr
inch per year (in/yr) miles per hour	1.609	kilometers per hour
	Specific capacity	
gallon per minute per foot [(gal/min)/ft)]	0.2070	liter per second per meter [(L/s)/m]
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Hydraulic gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
	Transmissivity*	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88). Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83). Altitude, as used in this report, refers to distance above the vertical datum. *Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [(ft^3/d)/ft^2]ft. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience

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Abstract

The Leetown Science Center is a research facility operated by the U.S. Geological Survey that occupies approximately 455-acres near Kearneysville, Jefferson County, West Virginia. Aquatic and fish research conducted at the Center requires adequate supplies of high-quality, cold ground water. Three large springs and three production wells currently (in 2006) supply water to the Center. The recent construction of a second research facility (National Center for Cool and Cold Water Aquaculture) operated by the U.S. Department of Agriculture and co-located on Center property has placed additional demands on available water resources in the area. A three-dimensional steady-state finite-difference ground-water flow model was developed to simulate ground-water flow in the Leetown area and was used to assess the availability of ground water to sustain current and anticipated future demands. The model also was developed to test a conceptual model of ground-water flow in the complex karst aquifer system in the Leetown area. Due to the complexity of the karst aquifer system, a multidisciplinary research study was required to define the hydrogeologic setting. Geologic mapping, surface- and borehole-geophysical surveys, stream base-flow surveys, and aquifer tests were conducted to provide the hydrogeologic data necessary to develop and calibrate the model. It would not have been possible to develop a numerical model of the study area without the intensive data collection and methods developments components of the larger, more comprehensive hydrogeologic investigation.

Results of geologic mapping and surface-geophysical surveys verified the presence of several prominent thrust faults and identified additional faults and other complex geologic structures (including overturned anticlines and synclines) in the area. These geologic structures are known to control ground-water flow in the region. Results of this study indicate that cross-strike faults and fracture zones are major avenues of ground-water flow. Prior to this investigation, the conceptual model of ground-water flow for the region focused primarily on bedding planes and strike-parallel faults and joints as controls on ground-water flow but did not recognize the importance of cross-strike faults and fracture zones that allow ground water to flow downgradient across or through less permeable geologic formations.

Results of the ground-water flow simulation indicate that current operations at the Center do not substantially affect either streamflow (less than a 5-percent reduction in annual streamflow) or ground-water levels in the Leetown area under normal climatic conditions but potentially could have greater effects on streamflow during long-term drought (reduction in streamflow of approximately 14 percent). On the basis of simulation results, ground-water withdrawals based on the anticipated need for an additional 150 to 200 gal/min (gallons per minute) of water at the Center also would not seriously affect streamflow (less than 8 to 9 percent reduction in streamflow) or ground-water levels in the area during normal climatic conditions. During drought conditions, however, the effects of current ground-water withdrawals and anticipated additional withdrawals of 150 to 200 gal/min to augment existing supplies result in moderate to substantial declines in water levels of 0.5-1.2 feet (ft) in the vicinity of the Center's springs and production wells. Streamflow was predicted to be reduced locally by approximately 21 percent. Such withdrawals during a drought or prolonged period of below normal ground-water levels would result in substantial declines in the flow of the Center's springs and likely would not be sustainable for more than a few months. The drought simulated in this model was roughly equivalent to the more than 1-year drought that affected the region from November 1998 through February 2000. The potential reduction in streamflow is a result of capture of ground water that would otherwise have been discharged to Hopewell Run or its tributaries as base-flow discharge. In addition, because evaporation is the only potential consumptive use of water by the Center, most of the water used is returned to Hopewell Run shortly after use, and the net effect on streamflow downstream of the facility is minimal.

Withdrawal of water from two hypothetical production wells used to represent housing subdivisions of approximately 300 and 500 homes each was simulated to assess the effect of possible suburban development on water availability in the Leetown area. For slightly above normal rainfall conditions, simulated withdrawals from the two production wells did not result in substantial drawdown in the vicinity of the Center's springs and well fields. An additional reduction of streamflow of 2.3 percent was predicted during slightly above normal hydrologic conditions. For a simulated drought, the hypothetical withdrawals resulted in an additional 5.9 percent capture of surface water, and an additional drawdown of 0.3-1.0 ft near Balch spring and 0.5-1.0 ft near Gray Spring. Actual long-term effects on ground-water levels and streamflow most likely would be less than that simulated because the ground-water flow model did not account for sewage-plant or septic-system return flows to streams or ground water in the area. Because the model simulates long-term average conditions (steady state), effects of short-term hydrologic conditions could be greater than those discussed in this report.

Introduction

The Leetown Science Center is a research facility operated by the U.S. Geological Survey (USGS) that occupies approximately 455-acres in the eastern panhandle of West Virginia near Kearneysville, West Virginia (fig. 1). The primary mission of the Center is to conduct research needed to restore, maintain, enhance, and protect aquatic species and terrestrial organisms and their supporting ecosystems. The Center is also the site of the National Fish Health Laboratory, where research is conducted on fish diseases, declining species, invasive species, genetics, aquaculture, and ecology. The Center is co-located with the U.S. Department of Agriculture (USDA) National Center for Cool and Cold Water Aquaculture (NCCWA). Large quantities of high-quality, cold ground water are needed to support operations at these two research facilities. In 2006, water for research operations at the facilities was obtained from three large springs on Center property. Two production wells provided additional water during periods of high demand and during periods of low spring yield in late summer and early fall. A third production well provides primarily water for restrooms, water fountains, and a dormitory. Continued operation of the facilities as well as possible expansion of research activities depend on locating additional sources of high-quality, cold water to augment existing supplies.

Purpose and Scope

This report presents results of a steady-state simulation of ground-water flow in the Leetown area. The model was developed to (1) test a conceptual model of ground-water flow in the Leetown area, (2) develop a budget of available ground-water resources for the Center, (3) define the potential area of recharge for the springs at the Center, (4) conduct pumping scenarios to simulate effects to the springs if additional wells were tapped to augment water supply to the Center, and (5) assess the potential effects of drought and suburban development on the availability of water to the Center.

Methods of Study

Various methods were used to develop the numerical ground-water flow model for the Leetown area. Extensive data from aquifer tests conducted in Berkeley and Jefferson Counties (McCoy and others, 2005a;b), including the Leetown area, were analyzed to provide the hydraulic data (transmissivity, hydraulic conductivity, and storativity) needed for model development. These tests were conducted as part of fracture-trace and lineament analysis projects to assess hydrogeologic factors controlling the distribution of high-yield wells in the complex karst aquifer system of the region.

A streamflow-gaging station (fig. 1) was constructed on Hopewell Run to provide discharge data for calibrating flow components of the model, for developing a budget of water resources, and to determine recharge for the Leetown area by hydrograph analyses (Rutledge, 1998). Because the station was constructed downstream of the Center, it represents the total flow of water from the watershed (except for a small diversion to a pond) in which the Center is situated and provides a good estimate of total water available to the Center. Data from the station for the period October of 2003-September 2005 were used to help verify the water budgets estimated by using the model. Flow-duration statistics estimated for the Hopewell Run streamflow gaging station were adjusted to account for the diversion. Seepage measurements were also made to assess channel gains and losses within the watershed, especially as streams crossed faults or other major structural features.

Water-levels were measured at 83 monitoring and private domestic wells in May through September 2004 to provide data for calibration of water levels simulated by the ground-water flow model. Aquifer tests conducted in the Leetown area as part of this study and a previous study of fracture traces in Jefferson County provided additional data for model development and calibration (McCoy and others, 2005a; and McCoy and others, 2005b).

LiDAR (light imaging detection and ranging) technology was used to prepare a digital elevation model of the Leetown area. The LiDAR imagery provided data with a resolution of approximately ± 1 meter. These data were then used to develop the ground-surface elevation of the upper layer of the ground-water flow model and to provide elevation data for the wells in which water-levels were measured for model calibration.

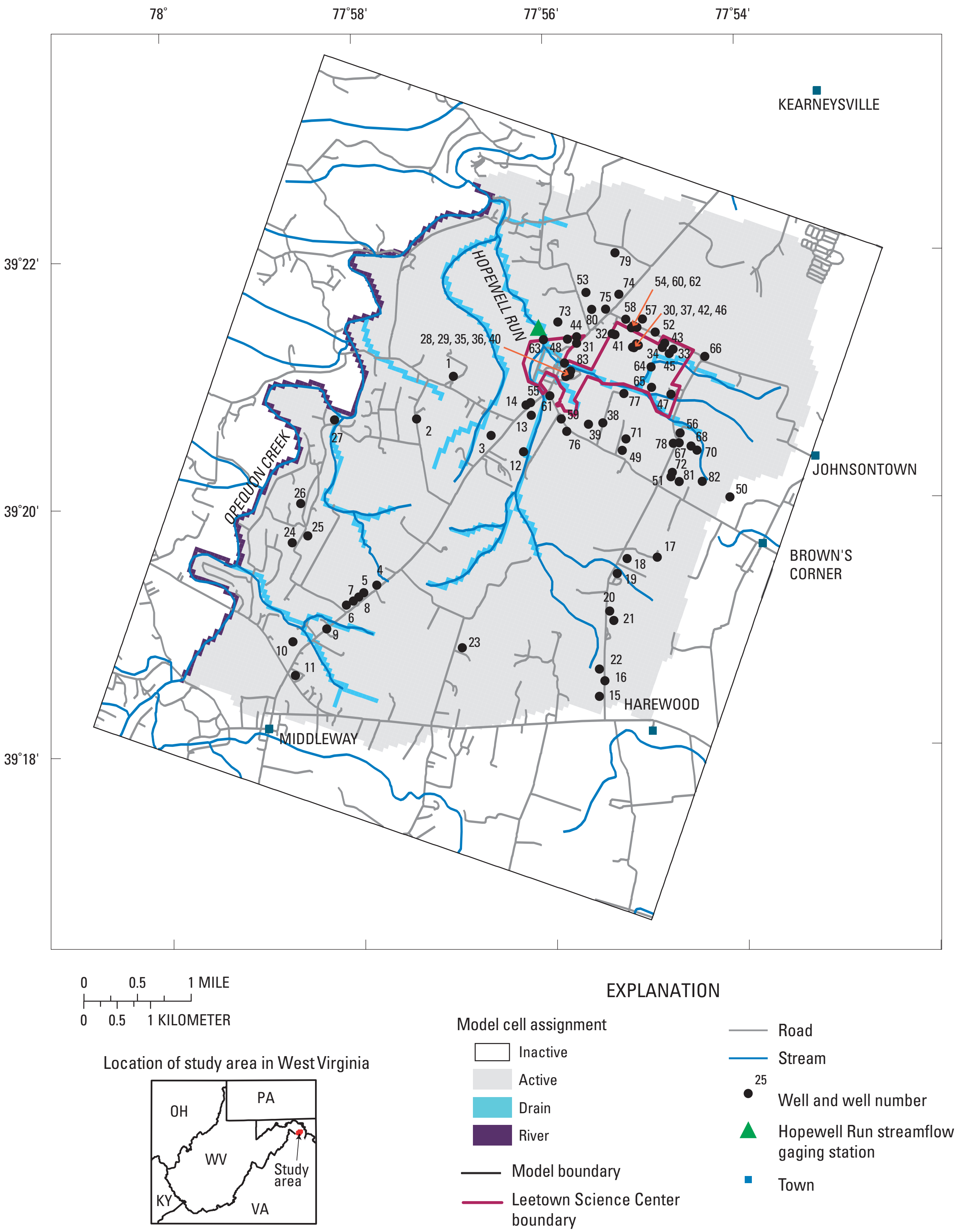


Figure 1. Location of study area and boundary conditions for the ground-water flow model of the Leetown area, West Virginia

The computer software package Visual MODFLOW, version. 4.0.0.131 (Waterloo Hydrogeologic, 2004), was used to develop a steady-state ground-water flow model of the Leetown area. Visual MODFLOW is a commercially derived graphical user interface to the USGS MODFLOW 2000 three-dimensional finite-difference ground-water modeling software (Harbaugh and others, 2000) and to MODPATH (Pollock, 1998), a USGS particle tracking software package. MODFLOW was used to simulate ground-water levels and provide a hydrologic budget for water in the Leetown area. The MODPATH interface was used for particle-tracking analyses to identify potential recharge areas to the springs and wells at the Center.

The use of a three-dimensional numerical model such as MODFLOW for simulating ground-water flow in a karst setting is a subject of much debate. Because MODFLOW assumes an equivalent porous media, its use in simulating ground-water flow in complex karst hydrogeologic settings may be inappropriate for many karst aquifers. This is especially true for cavernous and large conduit dominated karst systems such as that found in the Mammoth Cave area of Kentucky. MODFLOW, however, may be effectively used to simulate ground-water flow in the karst in the Leetown area. Although the aquifer does exhibit some karst features, sinkhole development is sporadic and caverns when encountered are limited in length and width. The majority of the rock mass in the region, especially in upland areas, is drained by an interconnected network of bedrock fractures with little or no solution development. The small conduits which develop, predominantly in low-lying areas, act as drains for the interconnected fracture network in the more areally extensive fractured rock mass. Thus, the conduits may be simulated as a network of interconnected drains by assigning higher hydraulic conductivities to these more permeable features and the aquifer can effectively be simulated by an equivalent porous medium approach using MODFLOW. It is necessary to simulate the anisotropy in the aquifer which can easily be done using MODFLOW.

Numerous simulations of ground-water flow in similar fracture-dominated karst aquifers have been effectively developed in similar hydrogeologic settings to that of the Leetown area using an equivalent porous medium approach and the MODFLOW software. White (2002) discussed the problems of simulating ground-water flow in karst settings but also indicated that the equivalent porous medium approach can work well when the locations of the major conduit drains are known or can be accurately estimated. Geologic mapping, surface geophysical surveys, and analysis of LiDAR imagery of the Leetown area provided reliable datasets to accurately map the location of the conduit drains. A realistic ground-water flow model could not have been developed without this data. A few examples of other equivalent porous media modeling of karst systems using MODFLOW include models developed for the Madison aquifer in South Dakota (Putnam and Long, 2005), the Edwards Aquifer in Texas (Lindgren and others, 2005), the Burlington-Keokuk Limestone in Missouri, the Malm Formation in Germany (Quinn and others, 2005), and the Boone-St. Joe Limestone aquifer in Arkansas (Unger and others, 2003).

Description of Study Area

The Leetown Science Center is in the Great Valley Physiographic Province in Leetown, West Virginia. The study area is approximately 4 miles southeast of Kearneysville, in Jefferson County, West Virginia. Hopewell Run and Opequon Creek (fig. 1), the major streams in the area, drain to the Potomac River. The Center encompasses approximately 455 acres, the USDA administers an additional 500+ acres east of the Center. Land-surface elevations in the study area vary from 410 to 630 ft above NAVD88. The ground-water flow model encompasses a larger area than that occupied by the Center to incorporate the various geologic and hydrologic features that control ground-water flow in the Leetown area. The model area is a 20-mi^2 area south of Kearneysville and includes the communities of Middleway and Harewood to the south, Johnsontown and Brown's Corner to the east, and several small communities along Opequon Creek to the west (fig. 1).

Previous Investigations

The relation between geology and ground-water supply and quality in the Great Valley of West Virginia was first discussed by Jeffords (1945a, 1945b). Further work by Graeff (1953) and Beiber (1961) defined the lithologic control that carbonate units have on the ground-water quality, quantity, and direction of flow in the aquifers of the Great Valley. Large springs discharging in excess of 1,000 gal/min from these carbonate units were correlated with the location of numerous faults in the area by Hobba and others (1972). Taylor (1974) concluded that systematic fracturing of the carbonate bedrock, attributed to a four-phase deformation history, is partially evident from topographic analysis of the area. He found well yields and spring locations in lowland areas to be related to structural features capable of transporting large quantities of water. Joints, faults, and fractures in lowland settings serve to move ground water downgradient although seasonal and annual fluctuations in storage and base flow to streams associated with these features can be high (Hobba, 1976; 1981). Base-flow stream discharge data, and water level data from Kozar and others (1991) and Shultz and others (1995), were used to calculate aquifer transmissivity values that range an order of magnitude, which was attributed to the anisotropic nature of fracturing in the carbonate rocks. Preferential flow in the direction of strike was verified by the dye-tracing work of Jones (1991), Kozar and others (1991), and Shultz and others (1995). Previous dye-tracing work by Jones and Deike (1981) at the Center showed the aquifer to dominantly consist of steeply dipping bedding planes and a diffuse network of fractures that may retard travel times and force circulation to depths below that common to other karst systems. In nearby Frederick County, Virginia, (Harlow and others, 2005) the conceptual model of Wolfe and others (1997) was applied to describe the influence of structural features on the spatial arrangement of various rock units and active karst development at moderate depths.

Flow patterns in the Great Valley are complex. The once flat-lying sedimentary rocks have been folded, faulted, and intensely weathered such that a variably thick layer of regolith overlies steeply dipping deformed bedrock units. Recharge in the form of infiltrating precipitation initially moves into the regolith where much of it is stored. Movement of water to the underlying bedrock occurs via leakage to open fractures, faults, and bedding planes or direct runoff into surficial karst features. Flow within the bedrock is controlled by the orientation and connectivity of the fracture system and location of solutionally enlarged conduits. The geologic structure in the regolith and continuous bedding planes serve to apparently force flow parallel to regional gradients (Jones, 1991). Frazier and others (1988) conducted a detailed surface-water assessment of the Center and adjacent property using watershed models primarily to assess the potential for flooding and long-term stability of engineered ponds proposed for construction. A major finding of the study, which is also supported by the work of Jones and Deike (1981), was that sufficient water for operations at the Center is not available during drought years; operations at the Center would have to be adjusted to compensate for reduced water availability during droughts or other periods of prolonged below average ground-water levels. Additional borehole log and surface geophysical data were collected by Mayle and Schnabel (1998) as part of geotechnical investigations prior to construction of the NCCWA facility.

Hydrogeologic Setting

The Center is uniquely situated with respect to the availability of abundant, high-quality, ground-water resources. The area is dominated by karstic carbonate rocks of Cambrian and Ordovician age. Low-permeability lithologic units such as the Martinsburg Formation and the Conococheague Limestone control ground-water flow by acting as barriers to water flowing down the hydraulic gradient and across the strike of the bedding. This retardation of cross-strike flow is especially pronounced in the Leetown area, where the bedding typically dips at steep angles. Geologic structures that disrupt the rocks in cross-strike directions, especially highly permeable fault and fracture zones, provide avenues through which ground water can flow laterally across or through strata with low primary permeability.

Geology

A geologic map of the Leetown area was published at a scale of 1:24,000 by the West Virginia Geologic and Economic Survey (Dean and others, 1990). This map was used as a basis for more detailed mapping of the area near the Center (fig. 2). This detailed mapping includes locations of bedrock contacts and the orientation of cleavage, fractures, and other structural features. Updates to the geologic interpretation include slight adjustments in the location of some of the bedrock contacts within the Hopewell Run drainage basin and the recognition of two west-northwest trending cross faults in the Leetown area (fig. 2). The bedrock in the Leetown area consists primarily of fractured limestone and dolomite of the Lower Ordovician and Upper Cambrian Conococheague Limestone; the Lower Ordovician Stonehenge Limestone, Rockdale Run Formation, and Pinesburg Station Dolomite; the Middle Ordovician New Market and Chambersburg Limestones; and the Upper and Middle Ordovician Martinsburg Formation (fig. 2). The geologic structure of the area is complex, with many thrust faults oriented parallel or sub parallel to the regional bedrock strike (approximately N. 20^{o} E.). Cross-strike longitudinal and oblique faults also occur at orientations of approximately N. 80^{o} W. and N. 65^{o} E., respectively (fig. 2). The rocks are tectonically deformed and many upright and overturned folds occur throughout the area. The overturned folds verge to the northwest, with limbs dipping steeply to the southeast. The variable permeability of the different lithologies, especially the more resistant Martinsburg Formation and Conococheague Limestone, together with geologic structure and topography, govern the pattern of ground-water movement through the study area (fig 2).

Joints, bedding, and cleavage within the bedrock also can exert control on ground-water flow patterns and rates. A compass rose diagram (fig. 3) clearly illustrates the dominant directions of joint planes within the surficial bedrock in the Leetown area. Two dominant joint directions are apparent: one oriented approximately normal to and the other oriented approximately parallel to the regional strike of bedrock. The joint set normal to the bedrock strike (cross-strike joints) trends in a range from about N. 90^{o} W. to N. 60 ^{o} W., and the joint set parallel to bedding (strike-parallel joints) trends in a range from about due north to N. 40^{o} E. The cross-strike joints may be over-represented in this sampling as a result of the linear geometry of the outcrops, which typically causes them to be better exposed than the strike-parallel joint set.

Bedding attitudes in the Center area are complex as a result of the tectonic events that occurred in the geologic past. Bedding varies from nearly flat-lying in some areas to nearly vertical in others. In some areas, the bedrock dips steeply toward the southeast, and in other areas, beds have been overturned as a result of complex folding within the bedrock.

Cleavage is produced by alignment of platey minerals in rocks under tectonic stress and commonly occurs in planes normal to the direction of maximum compression. Some fanning of cleavage direction with respect to the fold axes has been observed in the study area. In the Center area, cleavage is common in the Martinsburg Formation and in the Stonehenge Limestone, which has a silty component, especially within the massive, basal Stoufferstown Member. Cleavage in the Stonehenge

Limestone is so well developed, especially in the low-primary porosity Stoufferstown Member, that it completely obscures the bedding in places. The predominant attitude of cleavage planes in the Center area is a strike of about N. 20º E. and near-vertical dips to either the east or west, with eastward dips prevalent.

Although dissolution of limestone in karst areas is common, the Leetown area does not exhibit classic mature karst topography. Sinkholes are found in the study area, but they are sparse and confined primarily to the Conococheague Limestone (fig. 2).

Hydrology

Ground-water flow occurs predominately in diffuse fractures within the study area. Water that flows through the intricate network of lower-permeability diffuse fractures is collected over a broad area in higher-permeability conduit drains that primarily coincide with the major thrust, normal, and cross faults. Zones of high conductivity are also indicated by surface-geophysical and LiDAR data in some areas. These geophysical anomalies are most likely highly transmissive fracture zones but may be unmapped faults. Investigators who developed conceptual models of ground-water flow in the area (Kozar and others, 1991 and Shultz and others, 1995) recognized the importance of solutionally enlarged bedding planes in governing ground-water flow. The importance of cross-strike faults or other complex geologic structures, such as overturned or tightly folded structures, in controlling ground-water flow, was not fully realized until it was viewed in context with recent work (McCoy and others, 2005 a;b), and as a result of the detailed data collected for this investigation.

Ground-Water Levels

Knowledge of ground-water levels is critical to understanding ground-water flow processes in the complex karst flow system in the study area. Topographic variability in water levels is pronounced, with shallower water levels (sites Jef-0584, 590, 591, 594, 595, 600, 602, 656, and 657; app. 1) common in valleys and topographic depressions and deeper water levels (sites Jef-0585-587, 589, 592, 593, 596-599, and 601; app. 1) in hillside and hilltop settings. Water-levels also show substantial seasonal variability, they typically are lowest in late summer to early fall and highest in winter to early spring (app. 1 and fig. 4).

The average maximum and minimum monthly water levels for well Jef-0526 for the period of record (1985-2005) occur respectively in April (average April water level is 21.39 ft below land surface (bls)) and September (average September water level is 23.06 ft bls). In 2003 water levels in the Leetown area were well above normal for the entire year as a result of above average precipitation during the period (table 1). The water-level hydrograph for well Jef-0526 (fig. 4) illustrates an almost instantaneous response of ground-water levels to precipitation.

Hydraulic gradients can be determined by comparing water levels in wells completed at different depths within the aquifer. Eight well pairs (Jef-0588/600, 590/595, 589/598, 587/596, 586/599, 601/597, 585/597, and 592/597) were installed as part of this study. Typically, water levels in the well pairs differed only slightly, probably because the deeper wells were constructed as open-rock boreholes which reflect a composite hydraulic head controlled primarily by the more permeable fractures typically encountered in the upper portion of the borehole. As a result of the complex hydrogeologic setting of the study area, composite heads in wells, and a general lack of quantitative vertical-head distribution data over the model domain, the model was not calibrated with respect to vertical hydraulic gradients. However, predicted vertical heads seem reasonable based on the limited data available.

Ground-Water Recharge

An accurate assessment of ground-water recharge in the study area is needed to develop a realistic ground-water flow model. A streamflow-gaging station was installed on Hopewell Run (fig. 1) in April 2003 to provide data for model calibration and to estimate ground-water recharge. Streamflow data for a 30-month period (app. 2) was evaluated by hydrograph analysis to estimate recharge (Rutledge, 1998) and to provide base-flow discharge data. As a result of the analysis, an average value of 16.5 inches per year (in/yr) of recharge (table 2) was estimated for the Hopewell Run watershed for the period October 2003-September 2005.

Precipitation records for the nearby Martinsburg airport (National Oceanic and Atmospheric Administration, 2006) indicated annual precipitation totals of 53.94, 46.41, and 30.38 in/yr for 2003, 2004, and 2005 respectively (table 1). Long-term mean annual precipitation (1891-2004) for the airport is 39.39 in. (National Oceanic and Atmospheric Administration, 2004). Mean annual precipitation for the 2-year period October 2003-September 2005 of 38.6 inches is within 1 in. of the long-term average. Therefore, the median annual recharge of 16.5 in/yr for the period September 2003 through October 2005 was used for development and calibration of the ground-water flow model and represents an average recharge rate for the Hopewell Run watershed. Ground-water levels (app. 1 and 3) were also measured during periods considered typical of the 24-month period to provide an acceptable data set of ground-water-level data for model calibration.

Because streamflow data were available only for the Hopewell Run at Leetown gaging station for a 30-month period, recharge was also estimated for the Opequon Creek at Martinsburg. Streamflow data has been collected at this station since1947, and provide a measure of the variability of streamflow and ground-water recharge during average and drought

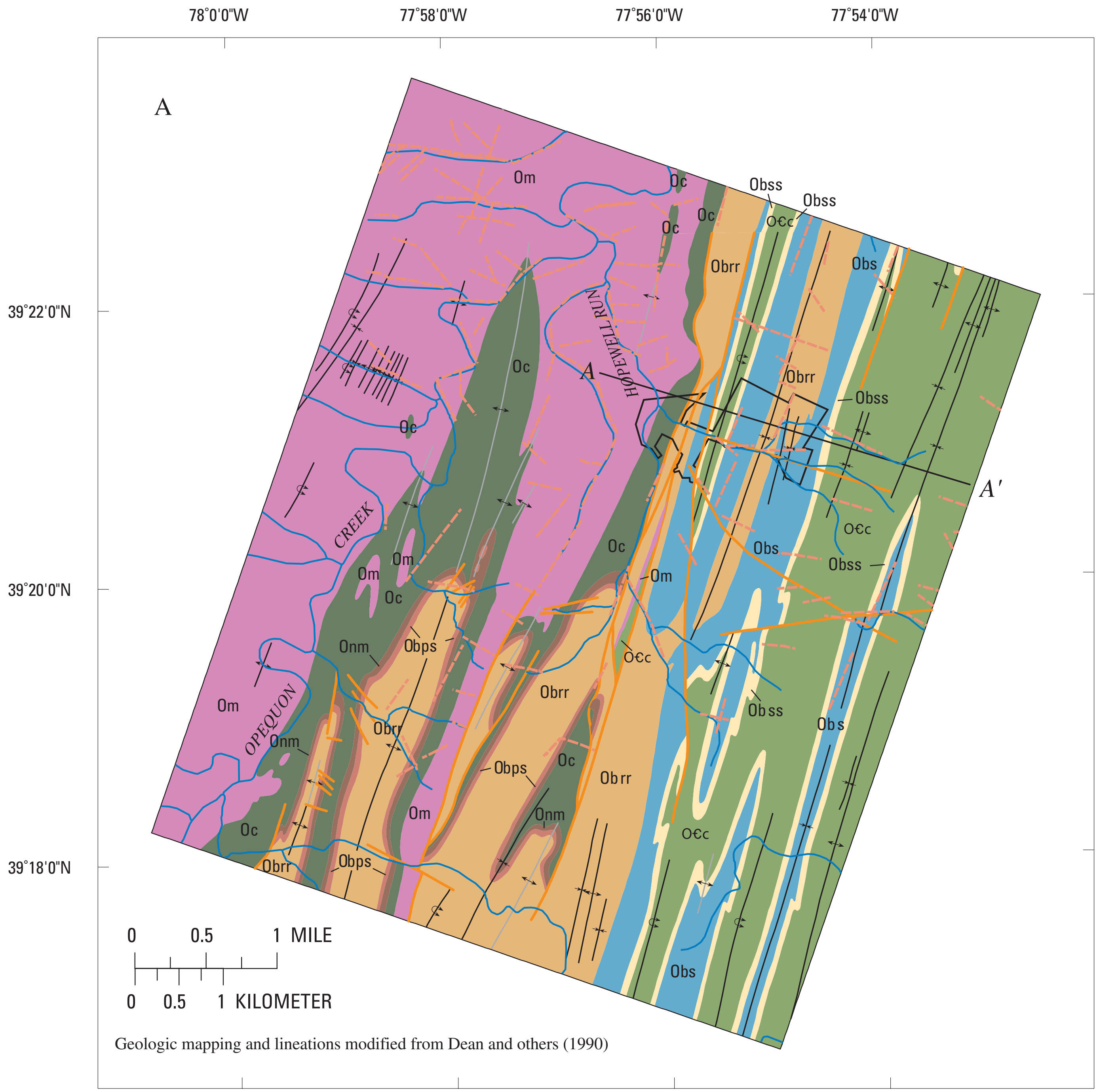


Figure 2a. Geology of the study area, with structural features and location of the Leetown Science Center, West Virginia

periods. The long-term average recharge for the Opequon Creek watershed was estimated to be 9.8 in./yr (Kozar and Mathes, 2001). The recharge rate for the Hopewell Run watershed is higher as a result of the larger proportion of limestone bedrock which outcrops in the Hopewell Run basin. In contrast, the Opequon Creek watershed has substantial outcrops of the less permeable Martinsburg Formation. Meteorological records (Cornell University, 2006) indicate the most recent drought in the area occurred during the period from November 1998-January 2000. This was the fourth most severe drought on record dating back to 1895, and was the longest, lasting for approximately 16 months. An analysis of potential recharge for the Opequon Creek watershed (table 2), to which Hopewell Run drains, was conducted to estimate recharge for the Hopewell

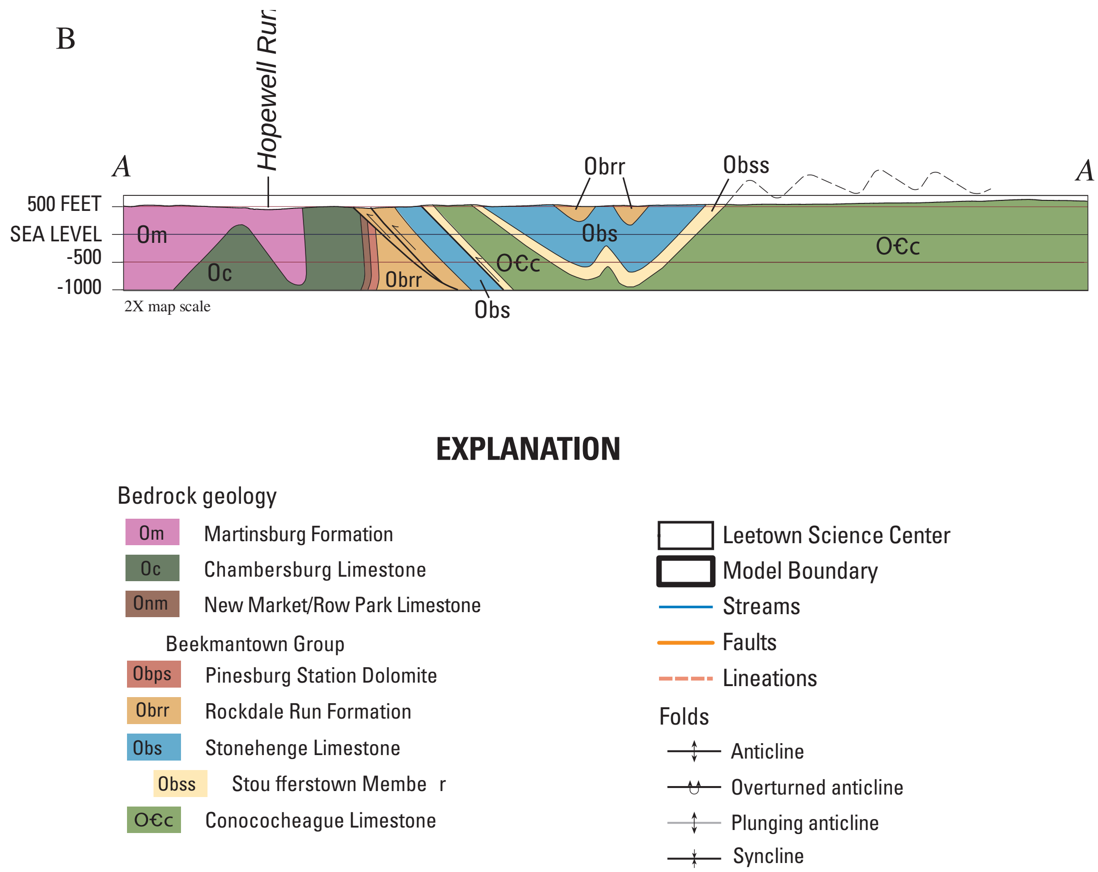


Figure 2b. Cross section of the study area.

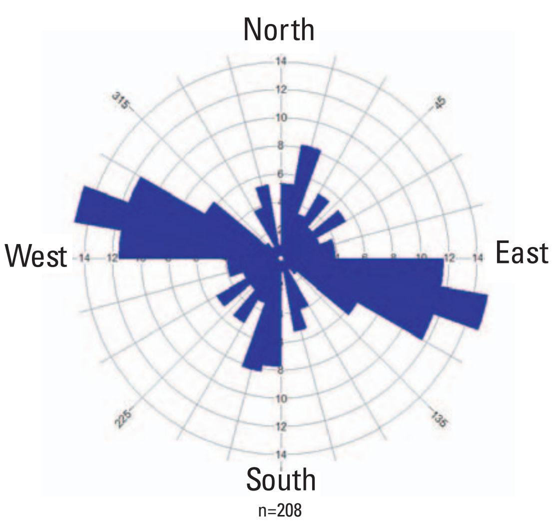


Figure 3.—Compass rose diagram showing the dominant directions of joints in the surficial bedrock of the USGS Leetown Science Center, West Virginia. [Joint sets were weighted by counting closely spaced joint sets three times, moderately spaced sets two times, and widely spaced sets one time. This system approximates the importance of each set relative to the volume of the rocks. Interval is 10 degrees. Numbers in diagram are percent of total. n, number of joints]

Run watershed during droughts. Estimated ground-water recharge for the Opequon Creek watershed for the 1999 drought was 5.69 in/yr. Extrapolating data from Opequon Creek to Hopewell Run results in a recharge rate of approximately 8.3 in/yr for the Hopewell Run watershed during the 1999 drought. This value was used in the drought simulation (discussed later in this report). Because low-flow statistics for the eastern panhandle of West Virginia clearly show that streamflow during the period 1970-2002 was anomalously high (fig. 5) when compared to the period 1930-1970 (Wiley, 2006), realistic water-use planning would need to be based on low-flow availability.

Hydraulic Properties

Hydraulic properties are the basic components used to develop a ground-water flow model and include aquifer transmissivity, hydraulic conductivity, saturated thickness, and specific yield (storativity). Transmissivity is a measure of an aquifer's ability to transmit water and generally is defined as the rate at which water is transmitted through a unit width of aquifer under a unit hydraulic gradient (Gary and others, 1973). Saturated thickness is the proportion to which an aquifer is saturated with ground water. Hydraulic conductivity is transmissivity divided by the saturated thickness of the aquifer. Specific yield is a measure of the aquifers ability to store water and is defined as the ratio

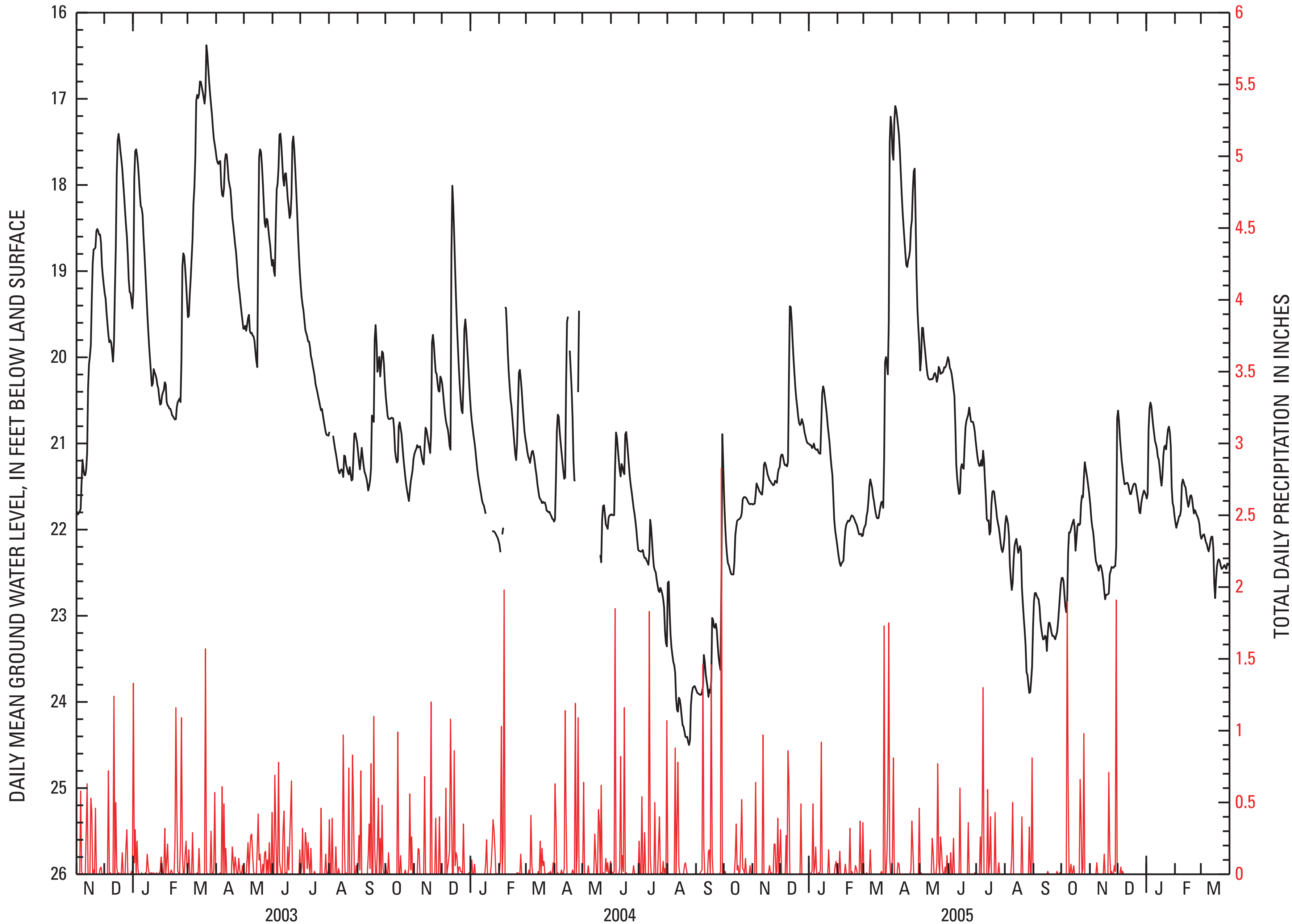


Figure 4. Water-level hydrograph for well Jef-0526 and precipitation at Gray Spring (Jef-0521S), November 2002-November 2005, Leetown, West Virginia [Locations of this well and a spring are shown on fig. 1]

Table 1. Monthly precipitation at the Eastern West Virginia Regional Airport, Martinsburg, West Virginia, 2003-05.

[Data obtained from National Oceanic and Atmospheric Administration website **accessed March 1, 2006, at url** *http://www.erh.noaa.gov/er/lwx/climate/mrb/*]

Month	Year 2003 (inches)	Year 2004 (inches)	Year 2005 (inches)
January	2.31	1.78	2.05
February	4.49	3.43	1.38
March	3.12	1.92	4.44
April	2.92	5.84	2.63
May	7.53	7.06	2.03
June	9.20	4.49	1.64
July	3.80	4.04	2.92
August	3.43	2.13	2.92
September	6.50	7.75	0.14
October	3.01	2.38	5.29
November	3.75	3.11	3.63
December	3.88	2.48	1.31
Annual total	53.94	46.41	30.38
Departure from total	14.55	7.02	-9.01

[1]Departure is based on 113 years of precipitation data.

of the volume of water a given mass of saturated rock or soil will yield by gravity to the volume of that mass (Gary and others, 1973). Specific yield and storativity are similar measures except that specific yield applies to unconfined aquifers and storativity applies to confined aquifers. These hydraulic properties were determined by conducting many single- and multi-well aquifer tests within the bedrock units in the Leetown area. These same units crop out at the surface over a broad area in both Jefferson and Berkeley Counties. Aquifer-test data from two lineament- and fracture-trace analyses (McCoy and others, 2005a and 2005b), which include data for the Leetown area, were used to determine the typical hydraulic properties of the geologic formations in the model area. Statistical analyses of these data indicate that three of the eight geologic formations that are surficially exposed in the study area have characteristically low (<1.0 ft/d) hydraulic conductivities (table 3).

These formations are the Martinsburg Formation, Conococheague Limestone, and New Market limestone, whose estimated hydraulic conductivities for the three layers of the model range from 0.135 to 0.35, 0.375 to 1.50, and 0.13 to 0.32 ft/d, respectively. The low hydraulic conductivity of these units (table 3) controls ground-water flow in the study area, acting as barriers to flow. Solution enlargement of fractures along major fault zones (simulated hydraulic conductivity ranging from 105-420 ft/d), and along minor fault and fracture zones and the contact between the Conococheague and Stonehenge Limestones (simulated hydraulic conductivity ranging from 18-76 ft/d) results in enhanced permeability along these paths, allowing them to act as drains for water to flow easily through or across the less permeable units. The cross-strike faults and some of the oblique faults, both of which cross bedrock at high angles, are especially effective as conduit drains for ground water.

Surface-Geophysical Data

In addition to geologic mapping of the Leetown area, a surface-geophysical survey was conducted to provide additional information on subsurface characteristics of the bedrock. The technique employed was audio magneto-tellurics (AMT), a geophysical method that provides lateral and vertical profiles of resistivity of the soil and bedrock. Electrical resistivity is a measurable physical property of the Earth that varies widely in both the horizontal and vertical dimensions. This range of resistivities is caused by a large number of physical parameters such as rock porosity, temperature, lithology, fluid, and electrolyte content. It was employed in the Leetown area to determine the variability of bedrock resistivity (both horizontally and vertically) within the aquifer and to identify potential resistivity anomalies that may indicate the presence of fracture zones or faults not readily apparent from geologic mapping alone.

AMT soundings are made to determine variations in the electrical resistivity of the earth with depth (Cagniard, 1950, 1953; Wait, 1962; Keller and Frischknecht, 1966; Hoover and Long, 1976; Hoover and others, 1976, 1978; Dmitriev and Berdichevsky, 1979; Vozoff, Keeva, 1991). The AMT method uses natural-source multi-frequency electromagnetic signals that result from lightning or atmospheric disturbances (sferics) as an energy source. For this survey, a controlled-source transmitter was used to supplement natural source energy when signal strength was low. Low natural source energy levels, in the middle frequency band of the instrument, can cause errors in the impedance estimates.

These AMT soundings consist of electric and magnetic field measurements over a range of frequencies from 10 to 100,000 Hertz (Hz) with fixed receiver and transmitter locations. The distribution of currents induced in the earth depends on the Earth's electrical resistivity, its magnetic permeability, and the frequency measured. Because low-frequency signals penetrate to greater depths than high-frequency signals, measurements of the electromagnetic (EM) response at several frequencies provide information on the variation of resistivity at depth. In this case a series of soundings whose data are inverted are joined together to form a profile or line of measurements approximately normal to the structure.

Table 2a. Quarterly estimates of ground-water recharge in inches for the Hopewell Run and Opequon Creek watersheds with statistical rank (highest to lowest) of annual totals.

[ind, indeterminate; water year, the period from October 1st through September 30th, designated by the calendar year in which it ends].

Water year	Oct-Dec	Jan-Mar	Apr-June	July-Sept	Annual total	Statistical Rank
			Hopewell Run At Leetown, WV[2]			
2003	ind.	ind.	8.35	2.61	ind.	ind.
2004	6.46	5.21	6.01	3.54	21.22	1st
2005	3.48	5.76	1.65	0.97	11.86	2nd
Median	4.97	5.49	6.01	2.61	16.54	
Mean	4.97	5.49	5.34	2.37	16.54	
			Opequon Creek near Martinsburg, WV[3]			
2003	3.75	6.33	5.68	2.86	18.62	2nd to 3rd
2004	4.77	3.93	4.42	2.92	16.04	3rd to 4th
2005	3.25	5.02	1.05	1.10	10.42	16th to 17th
Median	3.75	5.02	4.42	2.86	16.05	
Mean	3.92	5.09	3.72	2.29	15.02	

[2]Statistical analysis based on period from October 2003 to September 2005.

[3]Statistical analysis based on period from January 1948 to December 2004.

AMT soundings made during the spring of 2003, 2004, and 2005 (fig. 6A) in the Leetown area were recorded using a Geometrics EH-4 system. No vertical magnetic field (H_Z) data were recorded. Initially, more than 2,000 frequencies were collected and then reduced to approximately 40 frequencies for each of the two directions from 10 to 100,000 Hz. The magnetic field sensors, electric field sensors, buffers, and pre-amplifiers for both systems include a 60-Hz notch filter to reduce power line interference.

In this survey, the sounding locations were assessed prior to and after data collection. Sites were chosen so that stations were at least 100 meters from power lines. Background electric and magnetic fields were monitored prior to recording data and stations were moved if the static fields were above 250 mV on the E-lines or 150 nanoTeslas (nT) on the magnetic coils. AMT stations LT01, LT02, and LT13 collected on Center property, were not used because they are parallel sensor test sites.

Even with the uncertainty of interpreting one-dimensional electromagnetic data in a three-dimensional environment the electrical sections correlate well with the detailed mapped geology and local hydrology (fig. 6a, 6b, and 6c). AMT profiles and maps of one-dimensional inverted data show areas of higher and lower resistivities coincident with the prevailing geologic strike of N. 20^o E. Examples include low resistivities measured on a syncline, an anticline, near mapped faults, and mapped thrust faults (fig. 6b and 6c). Springs on Center property appear as low resistivity areas as a result of the increased porosity and fluid content of the rock.

The resistivity profiles resulting from the AMT survey correlated well with borehole-geophysical data, bedrock transmissivity of the various geologic units, and geologic structure in the study area. The AMT survey was able to identify subsurface faults and fracture zones, especially the more conductive water-bearing faults and fracture zones, one of which had not been identified by geologic mapping. The major cross faults that traverse the Center property are readily identified on the AMT profile (fig. 6B) as are previously unidentified anomalies (probable fault or fracture zones) that parallel the cross fault in the northern part of the study area and coincide with a synclinal structure. The data also are verified by linear features apparent in a LiDAR shaded relief digital elevation model (DEM) (fig. 6d).

Table 2b. – Quarterly estimates of ground-water recharge in inches for the Opequon Creek watershed with statistical rank (highest to lowest) of annual totals.

[ind, indeterminate].

Calendar Year	Jan-Mar	Apr-June	July-Sept	Oct-Dec	Annual Total	Statistical Rank[4]
1948	1.62	2.17	0.90	4.84	9.53	20th
1949	3.71	2.12	1.45	1.56	8.85	26th
1950	3.01	1.84	1.52	3.66	10.03	17th
1951	6.01	2.65	1.26	0.57	10.49	16th
1952	4.02	4.28	1.49	2.58	12.36	13th
1953	5.03	2.40	0.83	0.72	8.99	24th
1954	1.34	0.98	0.45	1.83	4.60	55th
1955	2.14	0.91	2.00	0.80	5.85	51st
1956	3.41	1.23	1.23	2.30	8.17	32nd
1957	2.99	1.93	0.64	1.27	6.83	46th
1958	3.81	2.34	1.36	0.53	8.03	33rd
1959	1.18	1.81	0.56	1.34	4.89	54th
1960	3.51	2.27	1.09	0.49	7.36	43rd
1961	4.32	2.62	0.88	1.07	8.89	25th
1962	4.89	1.75	0.90	0.96	8.50	28th
1963	3.47	1.24	0.46	1.02	6.19	50th
1964	4.82	1.89	0.80	0.77	8.28	31st
1965	4.18	1.30	0.57	0.46	6.51	49th
1966	1.58	1.59	0.81	1.51	5.50	53rd
1967	3.26	1.18	1.43	1.96	7.84	35th
1968	3.95	1.55	0.81	1.21	7.52	40th
1969	1.17	0.83	0.93	0.77	3.70	57th
1970	2.44	3.29	1.29	2.51	9.53	20th
1971	5.27	2.26	2.17	2.69	12.38	12th
1972	4.77	5.86	1.03	4.60	16.26	3rd
1973	3.20	4.97	1.25	3.74	13.16	10th
1974	4.14	1.25	0.90	2.16	8.44	30th
1975	4.18	3.15	3.82	2.27	13.43	9th
1976	3.75	1.71	1.01	3.36	9.82	18th

Table 2b. – Quarterly estimates of ground-water recharge in inches for the Opequon Creek watershed with statistical rank (highest to lowest) of annual totals.—Continued

[ind, indeterminate].

Calendar Year	Jan-Mar	Apr-June	July-Sept	Oct-Dec	Annual Total	Statistical Rank[4]
1977	2.39	1.91	0.68	2.46	7.44	42nd
1978	5.09	1.65	2.60	1.71	11.05	15th
1979	6.06	2.63	2.14	3.87	14.70	6th
1980	3.46	2.99	1.19	0.83	8.46	29th
1981	1.14	1.66	0.86	0.84	4.50	56th
1982	3.84	2.57	1.33	1.01	8.75	27th
1983	3.11	4.46	0.71	3.56	11.84	14th
1984	10.42	1.03	1.71	2.17	15.32	4th
1985	2.45	1.22	0.90	3.11	7.68	37th
1986	4.37	1.26	0.54	1.61	7.78	36th
1987	2.46	3.44	1.63	1.90	9.44	22nd
1988	2.11	3.59	1.02	0.85	7.57	39th
1989	2.80	2.56	0.90	1.18	7.45	41st
1990	1.86	2.03	1.32	4.61	9.82	18th
1991	4.13	1.29	0.78	1.02	7.23	44th
1992	2.35	2.01	1.20	2.48	8.03	33rd
1993	7.61	2.75	1.34	3.31	15.02	5th
1994	8.20	1.16	1.51	1.55	12.41	11th
1995	2.63	1.83	0.53	2.68	7.66	38th
1996	7.51	4.12	6.18	6.15	23.96	1st
1997	4.23	1.36	0.98	2.66	9.22	23rd
1998	9.09	3.15	0.93	0.85	14.01	8th
1999	1.95	1.01	1.51	1.22	5.69	52nd
2000	2.75	1.55	1.55	0.96	6.81	47th
2001	3.16	1.46	1.06	0.91	6.60	48th
2002	0.86	1.49	0.86	3.75	6.96	45th
2003	6.33	5.68	2.86	4.77	19.64	2nd
2004	3.93	4.42	2.92	3.25	14.52	7th
2005	5.02	1.05	1.10	ind.	ind.	ind.
Max	10.42	5.86	6.18	6.15	23.96	
Min	0.86	0.83	0.45	0.46	3.70	

Table 2b. – Quarterly estimates of ground-water recharge in inches for the Opequon Creek watershed with statistical rank (highest to lowest) of annual totals.—Continued

[ind, indeterminate].

Calendar Year	Jan-Mar	Apr-June	July-Sept	Oct-Dec	Annual Total	Statistical Rank[4]
Median	3.51	1.91	1.06	1.71	8.46	
Mean	3.82	2.27	1.33	2.08	9.50	

[4]Statistical analysis based on period from January 1948 to December 2004.

Table 3. Measured values of transmissivity for geologic formations, faults, and fracture zones and estimated values of hydraulic conductivity assigned to specific layers within the ground-water flow model of the Leetown area, West Virginia.

[ft/d; feet per day; ft^2/d, feet squared per day; na, not applicable].

Geologic formation	Geologic formation identifier on fig. 2	Measured[5] median transmissivity (ft^2/d)	Estimated[5] layer 1 hydraulic conductivity (ft/d)	Estimated[6] layer 2 hydraulic conductivity (ft/d)	Estimated[6] layer 3 hydraulic conductivity (ft/d)	Simulated[7] layer 1 hydraulic conductivity (ft/d)	Simulated[7] layer 2 hydraulic conductivity (ft/d)	Simulated[7] layer 3 hydraulic conductivity (ft/d)
Major faults and fracture zones	na	40,000	600	200	160	420	210	105
Minor faults and fracture zones	na	8,000	100	40.0	32.0	76.0	38.0	18.0
Martinsburg Formation	Om	60	0.75	0.30	0.24	0.35	0.275	0.135
Chambersburg Limestone	Oc	780	9.75	3.90	3.12	8.00	4.00	2.00
New Market and Row Park Limestones and Pinesburg Station Dolomite	Onm	10	0.13	0.05	0.04	0.32	0.26	0.13
Rockdale Run Formation	Obrr	1,000	12.5	5.00	4.00	18.0	9.00	4.50
Stonehenge Limestone	Obs	500	6.25	2.50	2.00	12.0	6.00	3.00
Stoufferstown Member of Stonehenge Limestone	Oss	8,000	100	40.0	32.0	76.0	38.0	18.0
Conococheague Limestone	Cc	80	1.00	0.40	0.32	1.50	0.75	.375

[5]Transmissivity values in this table were acquired from single and multi-well aquifer tests conducted as part of this investigation and previous fracture trace investigations in Jefferson and Berkeley Counties (McCoy and others, 2005a and 2005b).

[6]Hydraulic-conductivity estimates were based on measured transmissivity, ratios of bedrock resistivity at specific depths, and average depths of wells in the Leetown area.

[7]Hydraulic-conductivity values assigned to specific geologic formations and layers within the ground-water flow simulation.

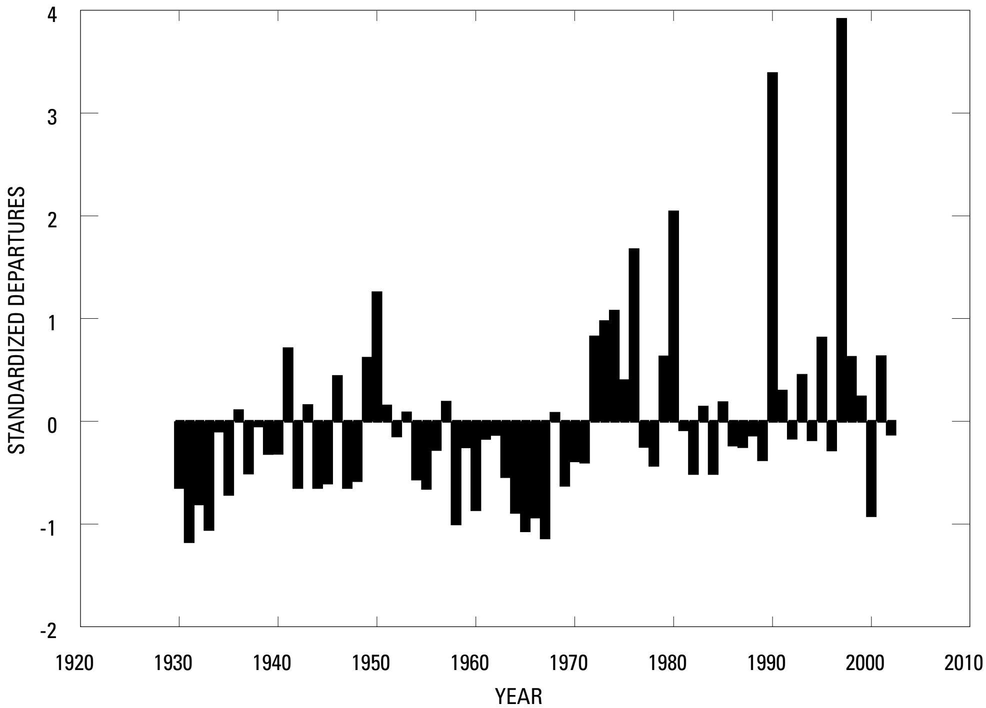
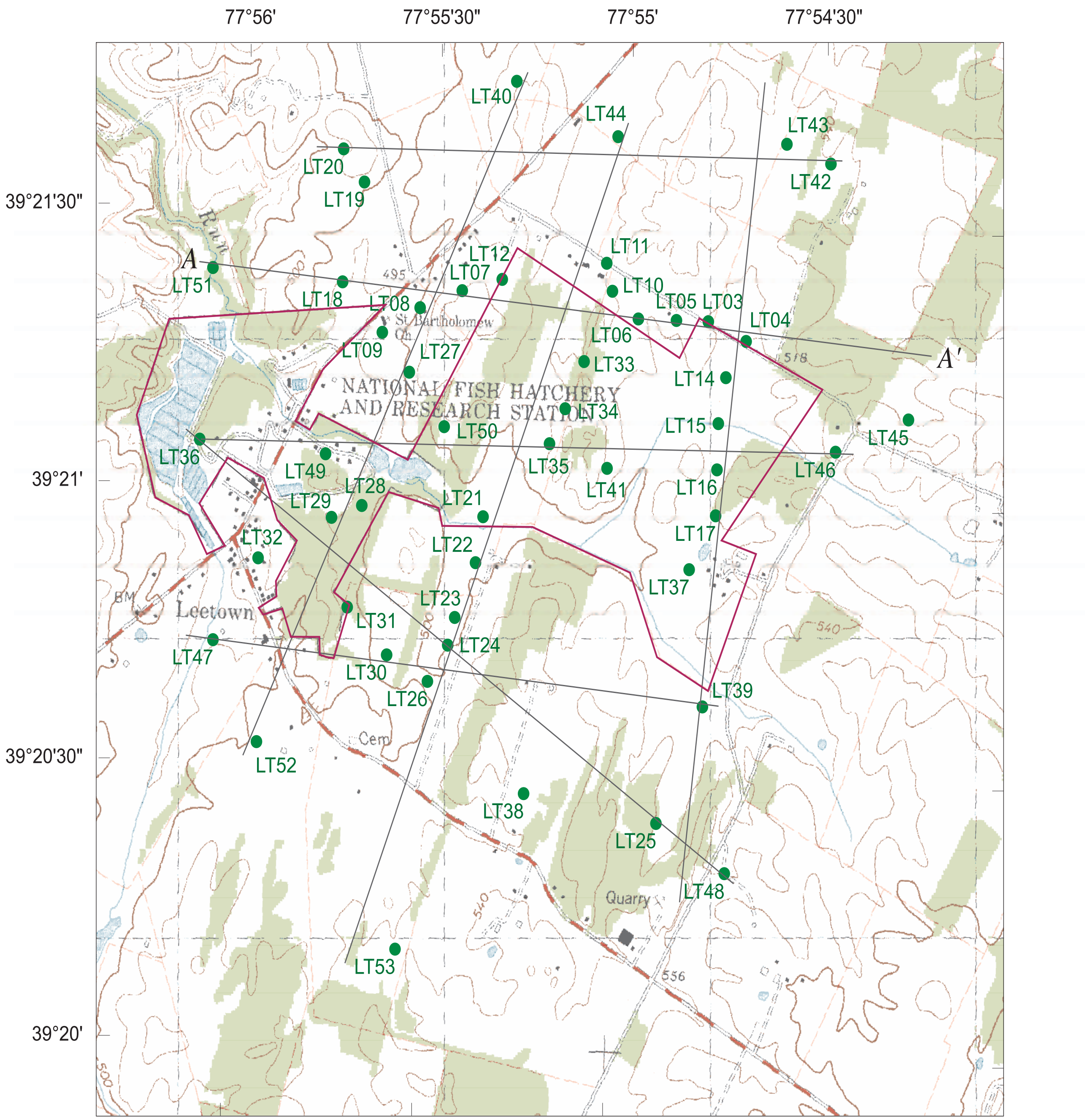


Figure 5. Average standardized departures of the minimum flows from the record-period average for 1930-2002 for five streamflow-gaging stations in the Eastern Panhandle region, West Virginia.

LiDAR Imagery

Light detection and ranging (LiDAR) data were acquired over Jefferson County, West Virginia by the Natural Resources Conservation Service (NRCS) from April 11 to April 18, 2005. The purpose of the data acquisition was to develop a high resolution (DEM) for the county for use in hydrologic applications. The data also were used to develop the ground-surface elevation simulated within the ground-water flow model. Data were acquired using an Optech ALTM LiDAR system at an altitude of 3,937 ft, an air speed of 161 mph, and a pulse rate of 50,000 Hz. Two land-based global positioning system (GPS) receivers were used during data collection, one at the Martinsburg airport and one in the eastern part of the county, to collect accurate elevation data for calibration of the LiDAR data. Post-processing of the data consisted of GPS trajectory and laser range corrections, first and last return extraction, and vegetation and building removal for a “bare-earth” surface model. Estimates of vertical accuracy during in-flight quality assurance tests over the Martinsburg airport averaged 0.102 ft root mean squared error (RMSE) in surface height. Data were converted to the North American horizontal Datum of 1983 (NAD 83) and North American Vertical Datum of 1988 (NAVD 88).

The NRCS asked the USGS to conduct a quality control study to provide an independent source of validation for the data collection. The USGS conducted ground surveys using a survey-grade differential GPS to measure surface heights of different land cover types in Jefferson County. The USGS found that the accuracy standard was met in 36 of 37 (97 percent) field-measured quality-control stations, and that the overall RMSE of the provided data was 0.09 meters vertically, well within the requested accuracy requirements. LiDAR data postings were processed to remove trees and buildings for a “bare earth” model. Data were imported from Arc-Info Grid export format tiles and joined together into a seamless grid. Grid tiles represented 1/16th of a standard 7.5-minute USGS quadrangle. Tiles covering the Middleway, W.Va. quadrangle and the Martinsburg, W.Va. SE and SW quarter-quadrangles were merged to create a 1-meter DEM encompassing the presumed surface and subsurface drainage area surrounding the Center. Vertical accuracy of the LiDAR data was actually slightly better than 1 meter, averaging approximately 0.61 m, or $\pm$ 2 ft. Comparison of LiDAR determined elevations with elevation data collected using a survey-grade GPS unit indicated potential maximum errors in excess of $\pm$ 5 ft in areas with heavy vegetation or steep slopes. Fortunately, such errors were mostly in peripheral areas of the model and were within acceptable limits for developing the model.



Base map from USGS 1:24,000 Middleway, W.Va. topographic quadrangle.

0 0.25 0.5 Mile

0 0.25 0.5 Kilometer

EXPLANATION

Leetown Science Center

Surface-resistivity cross section

LT53 Geophysical measurement station

Figure 6a. Locations of surface-geophysical measurement stations and surface-resistivity cross sections in the Leetown area, West Virginia

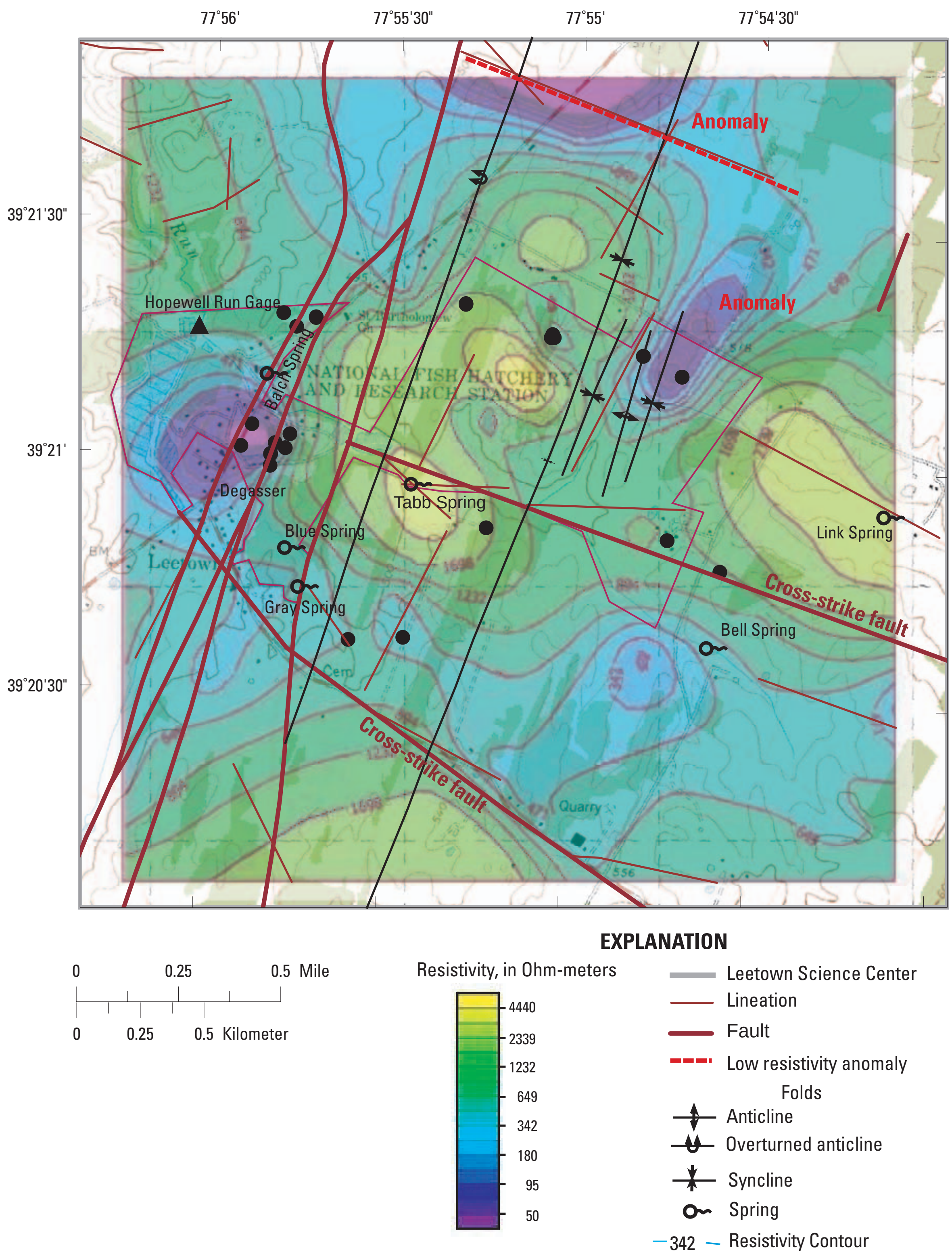


Figure 6b. Bedrock resistivity at an approximate depth of 197 feet below land surface showing low resistivity anomalies simulated as fracture zones within the ground-water flow model of the Leetown area, West Virginia.

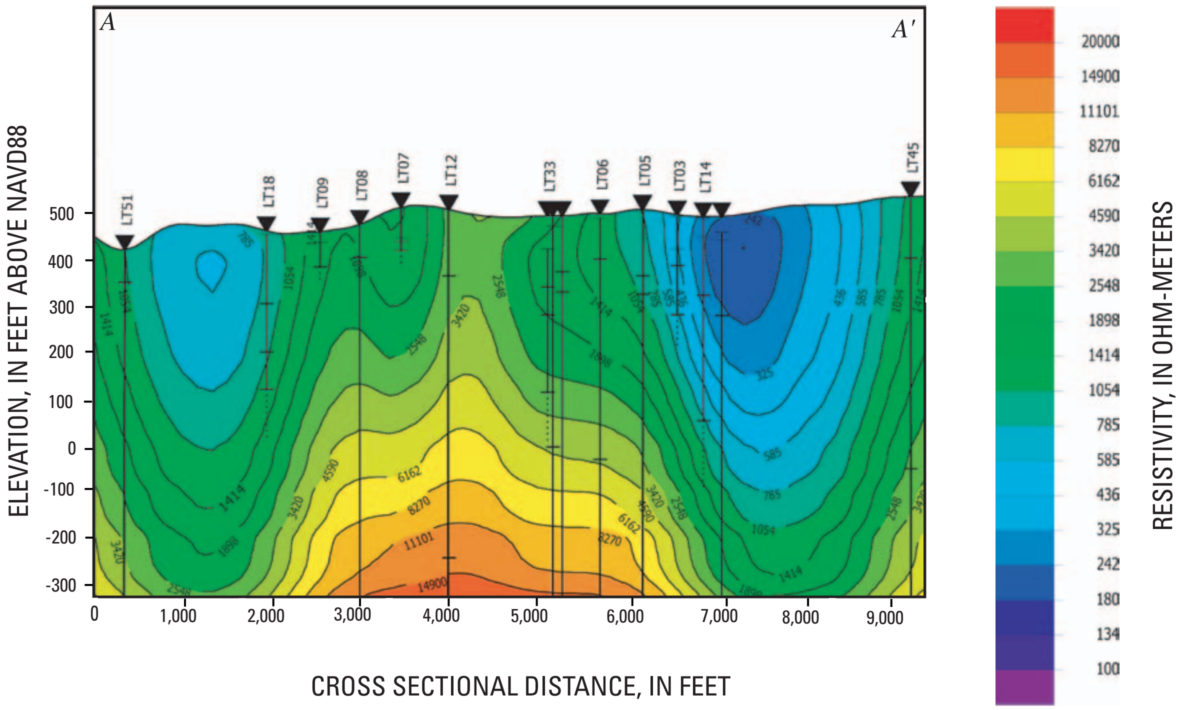


Figure 6c. Vertical geophysical cross section showing low-resistivity anomalies in the Leetown area, West Virginia. [Approximate cross section location shown on figure 2]

Ground-Water Withdrawals

Other than withdrawals from the Center's springs and well fields, there are no large commercial or industrial withdrawals of water or interbasin transfers of water in the Leetown area. Major withdrawals for the Center include those from Blue, Gray, and Balch Springs; production wells A and B (sites 85 and 84 in table 4); and the well that provides water for showers, toilets, sinks, and other domestic uses (site 86 in table 4). Average rates of water withdrawal for the Center for the simulation period are presented in table 4. The tabulated data provide a synopsis of the available sources of water to the Center and the likely long-term spring and well yields that can be expected under normal conditions. The data do not provide yield estimates for critical low-flow periods such as droughts. In the Leetown area, a large number of low volume ground-water withdrawals result from pumping ground water from domestic wells. Average water use in West Virginia is approximately 70 gallons per person per day. Because no public sewer or water lines are in the study area, most of the water withdrawn by homeowners is returned through infiltration of septic return flows to the shallow soil zone and to the underlying aquifer. Therefore, it was not considered necessary to simulate withdrawals for every domestic well in the Hopewell Run watershed. Only the major withdrawals were simulated in the ground-water flow model.

Conceptual Model of Ground-Water Flow

A previously developed conceptual model of ground-water flow (Kozar and others, 1991; Shultz and others, 1995) in the Jefferson and Berkeley County areas has been modified based on additional borehole and surface geophysical data and geologic mapping conducted as part of this investigation. Although recharge to sinkholes can occur, it is not a dominant process and ground-water recharge is areally distributed over a broad area. Recharge to sinkholes is a dominant process only when surface runoff occurs, typically as a result of intense localized rainfall. Precipitation falling on the surface quickly infiltrates the soil and regolith and percolates into the epikarst, a zone of intense weathering found present from land surface to a depth of approximately 60 ft (table 5). The hydrogeologic setting of the Leetown area is conducive to ground-water development but is limited by periods of low streamflow and ground-water levels. Large quantities of ground water are funneled through the area where the Center is located. This is also the primary reason for the presence of the highly productive springs that have historically supplied ground water for Center operations.

The epikarst is characterized by solutionally enlarged bedding planes and high-angle joints that allow rapid infiltration to the deeper bedrock aquifer. Below the epikarst, a zone of less weathered bedrock is present. This intermediate zone of moderately fractured bedrock typically does not exhibit the high density of solutionally enlarged conduits that are evident within the

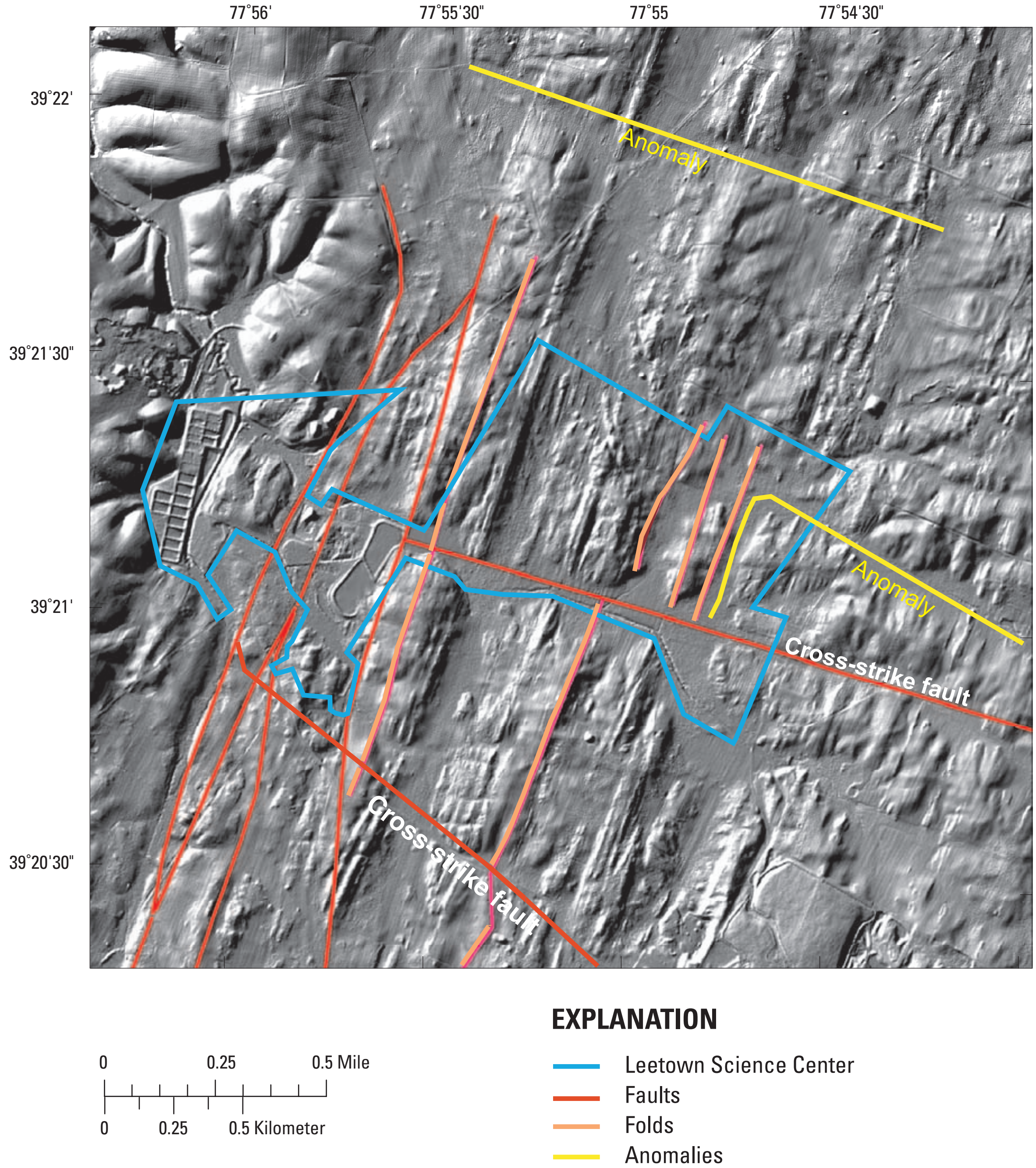


Figure 6d. LiDAR image showing low-resistivity anomalies, faults, and geologic structures and their correlation to fracture traces and lineaments in the Leetown Area, West Virginia. [LiDAR pixels have approximately 2 ft vertical resolution and 5 ft horizontal resolution]

epikarst. Hydraulic conductivity of the intermediate zone is less than that of the epikarst. Below a depth of about 250 ft, the aperture of bedrock fractures decreases substantially, and the estimated hydraulic conductivity, based on aquifer-test data, is approximately half that of the intermediate zone. Vertical hydraulic conductivity is poorly understood and was simulated within the model as approximately 1/10th the horizontal hydraulic conductivity. Sensitivity tests were used to evaluate the importance of variations in vertical hydraulic conductivity in the model.

The ground-water flow system is a triple-porosity system with negligible intergranular primary porosity, small micro fractures (matrix porosity) providing some storage of water, a dominant set of diffuse fractures providing most of the storage within the aquifer, and a system of solutionally enlarged fractures acting as drains for the intricate network of secondary-porosity features. Flow of ground water in the epikarst can be

Table 4. Ground-water withdrawal rates in 2004 and 2005 and yields of springs and wells at the Leetown Science Center, West Virginia.

[USGS, U.S. Geological Survey; gal/min, gallons per minute; >, greater than; <, less than; ft bls, feet below land surface; Jef, site-name prefix for Jefferson County, West Virginia]

USGS site name	Springs and wells	Probable well yield (gal/min)[8]	Median spring discharge (gal/min)	Current median withdrawal (gal/min	Well depth (ft bls)2	Well-bore open interval (ft bls)[9]	Comments
				Active sites			
Jef-0521S	Gray Spring		740	736			Principal water supply
Jef-0659S	Blue Spring		300	297			Principal water supply
Jef-0327S	Balch Spring		200	190			Principal water supply
Jef-0757	Domestic Well (#86)	>70		70	155	27.1 - 155	Production well with 50-percent duty cycle
Jef-0756	Well B (#84)	80		80	300	41.0 - 300	Production well, low-flow periods only
Jef-0755	Well A (#85)	>100		100	123	71.0 - 123	Production well, low-flow periods only
				Inactive sites			
Jef-0306S	Bell Spring		601	Unused			Perennial flow
Jef-0758S	Tabb Spring		94	Unused			Perennial flow
Jef-0586	USDA Fault Well (#87)	100-125		Unused	201	98.0 - 201	New production well, water turbid >125 gal/min
Jef-0752	New Dodson Farm Well (#89)	100-125		Unused	166	38.5 - 166	Possible new production well, water turbid >125 gal/min
Jef-0753	New Kaiser Farm Well (#88)	<200		Unused	121	39.5 - 121	New production well, water turbid >200 gal/min
Jef-0590	Ball Field Well (#90)	<100		Unused	160	38.5 - 160	Possible new production well, water turbid in spring

[8]Maximum well yields are much higher but use of water is limited by turbidity, which increases substantially at higher withdrawal rates.

[9]All wells are completed as open bedrock boreholes with an upper cased interval.

Table 5.-Summary of data from field and borehole geophysical logs for 18 wells completed in the Leetown area, West Virginia, showing probable depth of epikarst in the area.

[bls, below land surface; nd, not determined, +, yield may be higher but could not be quantified; na, not applicable; gal/min, gallons per minute; USGS, U.S. Geological Survey].

USGS well name	Drilled depth (ft bls)	Depth of clay layer (ft bls)	Depth to deepest void (ft bls)	Depth of weathered rock (ft bls)	Depth to bedrock (ft bls)	Total well yield (gal/min)	Depth of fractures yielding water (ft bls)	Probable epikarst depth (ft bls)
Jef-0590	160	0-10.0	131.0	na	10.0	5	35	38.0
Jef-0584	161	0-14.0	105.0	na	14.0	40	55 and 67	55.0
Jef-0591	105	0-10.0	91.0	na	16.5	>100	34, 49, 65, 71, and 78	60.5
Jef-0595	51	0-8.0	30.0	na	8.0	>21	nd	30.0
Jef-0586	201	0-4.0	155.0	na	4.0	300	31, 47, 61, 115, 131, and 155	61.0
Jef-0599	37.5	0-12.5	18.0	na	12.5	5	14	37.5
Jef-0587	410	0-22.0	39.5	22-26	26.0	18	115, 372, and 399	26.0
Jef-0596	101	0-22.5	No voids	na	22.5	7	90	22.5
Jef-0585	326	0-11.0	35.0	11-13	13.0	6	106 and 313	35.0
Jef-0592	321	0-18.0	No voids	18-20	20.0	22	37, 61, 71, and 133	38.0
Jef-0597	51	0-12.5	37.5	na	12.5	>35	nd	37.5
Jef-0589	260	0-20.0	52.0	20-25	25.0	20	29, 137, 170, and 250	30.0
Jef-0598	42	0-24.0	30.0	na	24.0	7	24	38.0
Jef-0588	220	0-12.0	216.0	12-28	28.0	300	41, 102, and 142	56.0
Jef-0600	79	0-16.5	66.0	16.5-18	18.0	100	25 and 70	57.0
Jef-0593	56	0-1.0	35.0	1-2	2.0	20	35	35.0
Jef-0594	41	0-3.0	24.0	na	3.0	20	16 and 27	24.0

rapid -- on the order of weeks, as indicated by results of tracer tests conducted in the area (Jones, 1997; Jones and Deike, 1981). This is especially true if flow is concentrated in solutionally enlarged conduits. Ground water in the intermediate zone is much older; estimates of ground-water age in the Great Valley carbonate rocks are on the order of 15 to 50 years (McCoy and Kozar, 2007). There are few data from which to estimate the age of ground water in the deeper portions of the aquifer. It is likely that ground water flows slowly at depths greater than about 300 ft. One chlorofluorocarbon (CFC) analysis of water from a 475-ft-deep well on the Center indicated an apparent ground-water age of approximately 50 years. Water from greater depths is likely much older.

Topography also has a major effect on ground-water flow. Depth to water typically is greater on hillsides than in valley or hillside settings. Upland areas are commonly formed from more resistive rock. These rock formations typically have lower hydraulic conductivities than the more permeable formations in lowland areas. The Conococheague Limestone and Martinsburg Formation, and to a lesser extent, the Row Park and New Market Limestones (fig. 2), are the principal lower permeability units and act as barriers to ground and surface water flowing down topographic gradients. Within the study area, regional ground-water flow is primarily from the topographically higher areas in the east toward Opequon Creek in the west. The low-permeability Martinsburg Formation and Conococheague Limestone are dominant controls on ground-water flow, impeding westward flow of ground water toward Opequon Creek. Water is forced to flow parallel to bedrock strike along solutionally enlarged faults, which dominate the area on which the Center is located. Although ground-water flow is impeded on its westward path, cross-strike faults, oblique faults, and associated fracture zones provide avenues along which ground water can flow either across or through the less permeable units.

Ground-Water Flow

When model calibration was completed, analyses of ground-water flow were conducted to (1) develop a water budget for the Leetown area to assess effects of current and future ground-water withdrawals on long-term water availability to the Center, (2) evaluate hydraulic heads simulated by the model to better understand ground-water flow in the watershed and to delineate the recharge areas to the Center's principal springs, (3) simulate drawdown from production wells and assess potential pumping effects on the Center's springs, and (4) assess effects of drought on water availability by reducing the recharge to the model and comparing simulated water levels for pumping periods to water levels simulated under pre-pumping conditions.

Numerical Model of Ground-Water Flow

The ground-water flow model prepared for this investigation is a steady-state simulation concentrated on the Leetown area but also incorporates a larger area to define hydrogeologic boundary conditions. The focus of the model is the 455-acre USGS Center and adjacent USDA land (fig. 1). The Hopewell Run watershed from its headwaters to the gaging station at Leetown (drainage area of 8.95 mi^2) was also an important part of the simulation. Areas of less importance include the minor tributary streams that drain to Opequon Creek and the area west of the Center, which includes areas where the Martinsburg Formation and Chambersburg Limestone crop out. These areas were included to provide distinct, easily delineated boundary conditions for the model and because of their importance in controlling ground-water flow in the Leetown area.

Design and Assumptions

The ground-water flow model is based on the conceptual model of ground-water flow previously discussed. It consists of three layers to simulate the epikarst zone; the primary intermediate zone in which most wells are completed; and the less fractured, deeper portion of the bedrock aquifer. Water-level and streamflow data collected from May through November 2004 provided the basis for development and calibration of the model.

Assumptions were made for areas where data were limited or unavailable (mostly peripheral areas of the model) and with respect to the overall depth reached by ground-water flow. Aquifer tests on and adjacent to the Center indicate that the faults that cross the area tend to have higher hydraulic conductivity (table 3) than the individual lithologic units. This area also exhibits hydraulic properties more characteristic of a homogenous, isotropic aquifer with multiple faults and regolith acting as a uniform aquifer system rather than as discrete fractures. Therefore, the area near the Center was simulated as a broad, highly conductive area within the model. Because no data were available to characterize the peripheral areas of the model, faults in these areas were assumed to exhibit hydraulic properties similar to those near the Center.

The minimum base elevation of the Potomac and Shenandoah Rivers near the study area is approximately 240 ft at their confluence in Harper's Ferry, West Virginia. Because rivers are the primary discharge zones in the region, it is unlikely that substantial ground-water flow occurs at depths much greater than the base level of these major rivers. However, the ground-water flow model was extended vertically to sea level (0 ft) to account for any deeper ground-water flow that may occur. The average depth of ground-water flow simulated was approximately 450 ft below land surface. Land-surface elevations simulated in the model range from a minimum of 395 ft above NAVD 88 in the northwestern part of the model along Opequon Creek to 628 ft above NAVD 88 in the northeastern part.

Grids, Layers, and Boundaries

The model grid extends from the Kearneysville area to the north (fig. 1), to Middleway to the south, and is bounded by Opequon Creek to the west and by bedrock ridges near Johnsontown and Browns Corner to the east. The grid consists of 160 rows by 143 columns, includes 22,880 individual nodes, and encompasses an area of approximately 24 mi^2. Each node represents a surface area of approximately 203 ft by 218 ft. Approximately one-third of the nodes in the model are inactive. Opequon Creek and Hopewell Run are the only major streams simulated in the model.

The model consists of three layers that represent the three layers in the previously discussed conceptual model of ground-water flow (Figure 7). Hydraulic conductivity is highest in the top layer (table 3) which represents the epikarst (fig. 8) and extends from land surface to a depth of 100 ft. The middle layer represents the fracture-dominated portion of the aquifer in which most wells are completed (fig. 9); it represents 200 ft of bedrock and was assigned hydraulic conductivities approximately 2.0 to 2.5 times lower than that assigned to layer 1 based on results of aquifer tests conducted in Jefferson and Berkeley Counties. The third and lowermost layer (fig. 10) represents mostly fractured rock with low permeability and little or no conduit development. This layer represents approximately 150 ft of bedrock, and was assigned hydraulic conductivities approximately half that of the middle layer based on results of resistivity surveys and aquifer tests. The lower layer of the model extends to sea level in most areas.

Three different boundary conditions were simulated in the model (fig. 1). No-flow cells were assigned to the ridges on the northern, eastern, and southern margins of the model. No interbasin transfers of water were documented in the study area and the no-flow cells represent topographic and hydrologic boundaries. Opequon Creek was simulated with river nodes (fig. 1). This border is not emphasized within the model and the use of river, stream, or drain nodes made little difference in the overall water budget produced by the model. Drain nodes were used to simulate the tributary streams to Opequon Creek and include Hopewell Run and its various branches (fig. 1). Drain nodes do not effectively simulate losing stream reaches but still provided reasonable estimates of water budgets for the Hopewell Run watershed. Use of river nodes to simulate the tributary streams would have been inappropriate as they would have created constant heads in the nodes affected. Simulation of tributaries as stream nodes also would have required additional data. It was especially important that areas near the Center be simulated as accurately as possible as much of the water-level and streamflow data in these areas provided the primary calibration data for the model.

Calibration

The ground-water flow model was calibrated to both streamflow and hydraulic heads (ground-water levels). The gaging station on Hopewell Run provided the streamflow data to which flows of the tributary streams were calibrated. The mean flow of Hopewell Run, for base-flow periods (May-November) in 2004 (app. 2 and table 6), when ground-water-level measurements were made for model calibration, was approximately 10.42 ft^3/s, or 900,288 ft^3/d. The zone budget subroutine in Visual Modflow was used to calculate the water budgets for the model. Results of the zone budget analysis indicated that the simulated flow in Hopewell Run at the gaging station was 891,370 ft^3/d or 10.32 ft^3/s. This represents a less than 1-percent difference between measured and simulated streamflow. Water levels measured in 83 wells provided the data for calibration of the hydraulic heads (ground-water levels) simulated with the ground-water flow model. Simulated and measured water levels are strongly correlated (fig. 11), with an r^2 (correlation coefficient) of 0.99, a normalized root mean square error of 2.9 percent, and a root mean square error of 4.6 ft. Two factors limited the accuracy of simulated water levels with respect to measured water levels. First, because the cost to survey levels to 83 separate wells was considered prohibitive, elevations for well measuring points were based on the LiDAR elevations and GPS locations. The average horizontal error for the well locations, based on the GPS data, was $\pm$ 10 -15 ft. The error associated with the LiDAR assigned elevations was typically $\pm$ 2 ft but exceeded $\pm$ 5 ft on many hilltops and areas with dense vegetation or tree cover. The second limiting factor was related to the calculation of the water level within a node at the node center by the Visual Modflow software. If the observation well in which a water level was measured is not located near the center of the node, the difference between the simulated and measured water levels can be substantial. This error is most pronounced in areas of steep terrain and can be as much as $\pm$ 20 ft at some locations. Fortunately, the areas where topographic effects were pronounced are not areas of emphasis for the model. Given the limitations of assigning exact elevations to wells and the error associated with topographic effects, the calibration results are well within acceptable standards.

Effective porosity for limestone aquifers in the Leetown area is not well documented. Estimates of specific yield for the same geologic formations in nearby Berkeley County range from 4.4 to 4.9 percent (Shultz and others, 1995) and would be similar to the total porosity. The effective porosity of the limestone rocks in the Leetown area would be similar, but would be substantially lower in deeper portions of the aquifer where fracture apertures are smaller. The specific yield gives an estimate of total porosity more for the shallow epikarst, where the water-level fluctuation on which the estimates are based occurs. Therefore, an effective porosity of 1 percent was used to simulate porosity in the deeper aquifer and within the model. The 1 percent effective porosity provided the best calibration of

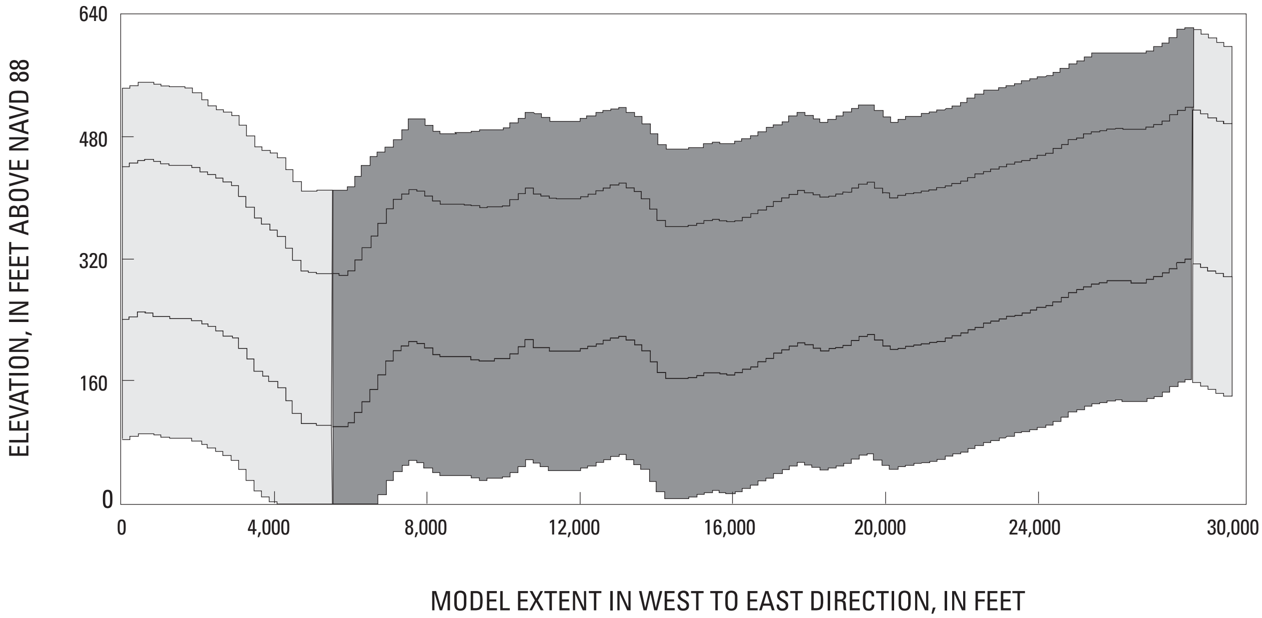


Figure 7. Layers simulated in the ground-water flow model of the Leetown area, West Virginia, and their approximate elevations referenced to NAVD 88. [Dark areas are active nodes and light areas are inactive nodes within the model]

simulated ground-water flow velocities within conduits to measured values of ground-water velocity determined from fluorometric dye tracer tests conducted for this study (table 7).

Sensitivity Analysis

The sensitivity of the model to variations in input parameters, including hydraulic conductivity, storativity, and recharge, was analyzed to provide a measure of the uncertainty of input-parameter values. Results of the sensitivity analyses show that the ground-water flow model is most sensitive to variations in recharge. Recharge for the model was based on analyses of the Hopewell Run streamflow hydrographs and was included in the sensitivity analysis to evaluate its importance for model calibration. The importance of recharge was expected and was the primary reason for the installation of the gaging station on Hopewell Run. Data from the gage provided a very good estimate of recharge for the model and eliminated the need to subjectively assign a recharge value. Estimates of hydraulic conductivity used in the model were based on aquifer-test data collected in the region. Although hydraulic conductivity data for some units (New Market and Pinesburg Station Formations) are sparse, the sensitivity analysis provided a measure of the effect of uncertainty of hydraulic conductivity values assigned to these and other geologic formations on model calibration.

Sensitivity analysis simulations were conducted by varying the input parameters by one third and comparing the root mean squared (RMS) and normalized RMS error to that of the calibrated model (table 7). The RMS and normalized RMS error for the calibrated model were 4.6 ft and 2.9 percent respectively, with a correlation coefficient between simulated and observed water levels of 0.99.

Overall, the model was not very sensitive to changes in hydraulic conductivity, especially for the units with high average hydraulic conductivity. Units with lower conductivity, such as the Conococheague Limestone and Martinsburg Formations, are exceptions. The ground-water flow model also was sensitive to the hydraulic conductivity assigned to the faults. Fortunately, aquifer-test data were abundant for the Conococheague Limestone and Martinsburg Formations and for wells completed in the fault zones. Ratios of horizontal to vertical hydraulic conductivity from 4:1 to 15:1 also were evaluated as a result of a lack of data for this parameter. Differences in calibration statistics for the various vertical hydraulic conductivity ratios were minimal, but the 10:1 ratio provided the best fit between simulated and field-measured water levels and was used for all simulations. The model was sensitive to anisotropy, with anisotropy of 2:1 in the direction of bedrock strike providing the best fit.

Water Budget

A ground-water budget is a simple mass balance of inputs to and outputs from a basin. The only input to the ground-water flow model was recharge from precipitation. Recharge estimated for the simulated period by analysis (Rutledge, 1998) of hydrographs for the Hopewell Run gaging station was 16.5 in/yr. No other inputs to the basin were evident in the Leetown area. Outputs from the basin include stream discharge, consumptive use of water from wells, evaporation of water from land and water surfaces, and transpiration of water by trees, grasses, and other vegetation. Precipitation was measured at the

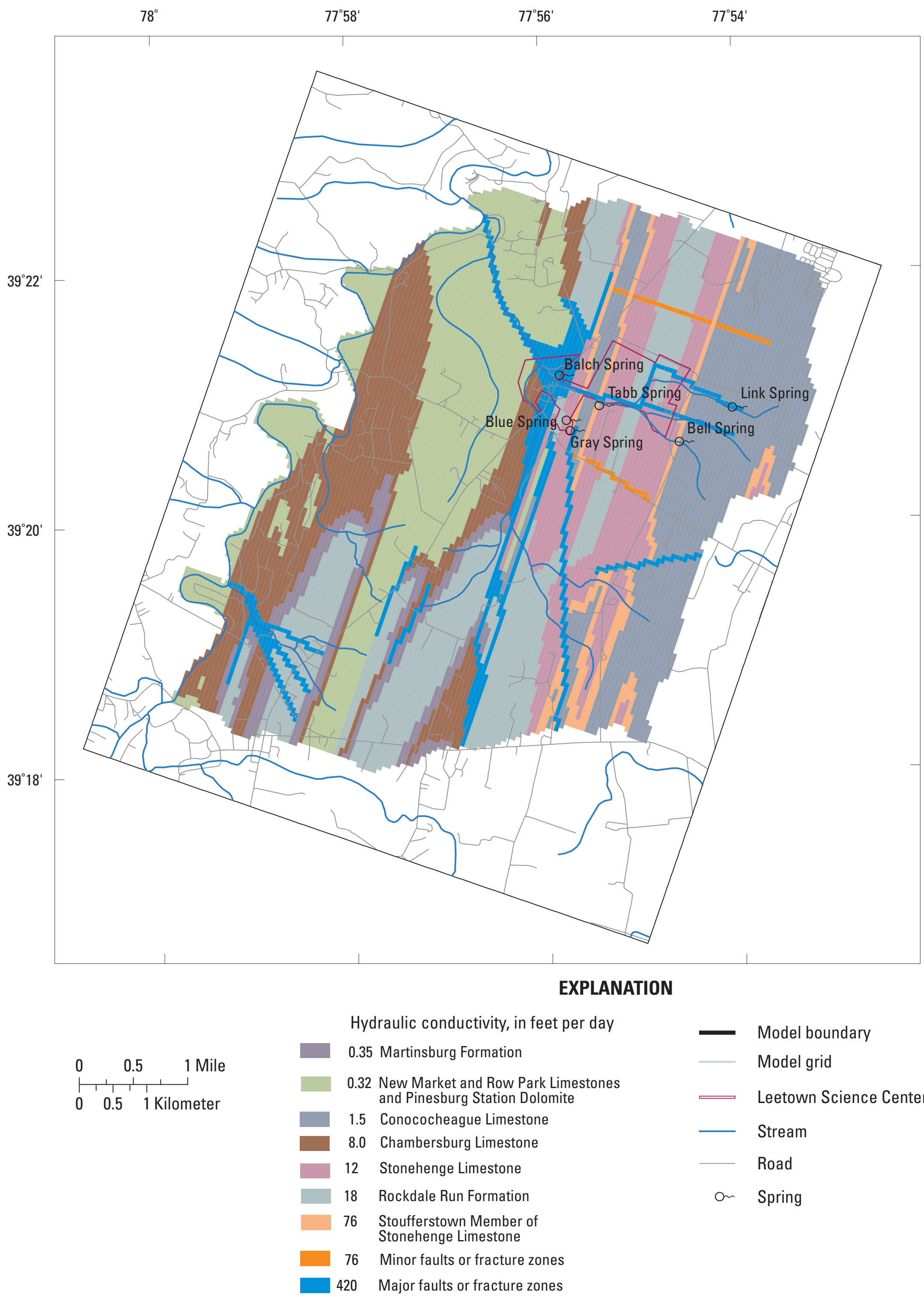


Figure 8. Hydraulic conductivity assigned to geologic formations, faults, and fracture zones in the upper layer of the ground-water flow model of the Leetown area, West Virginia.

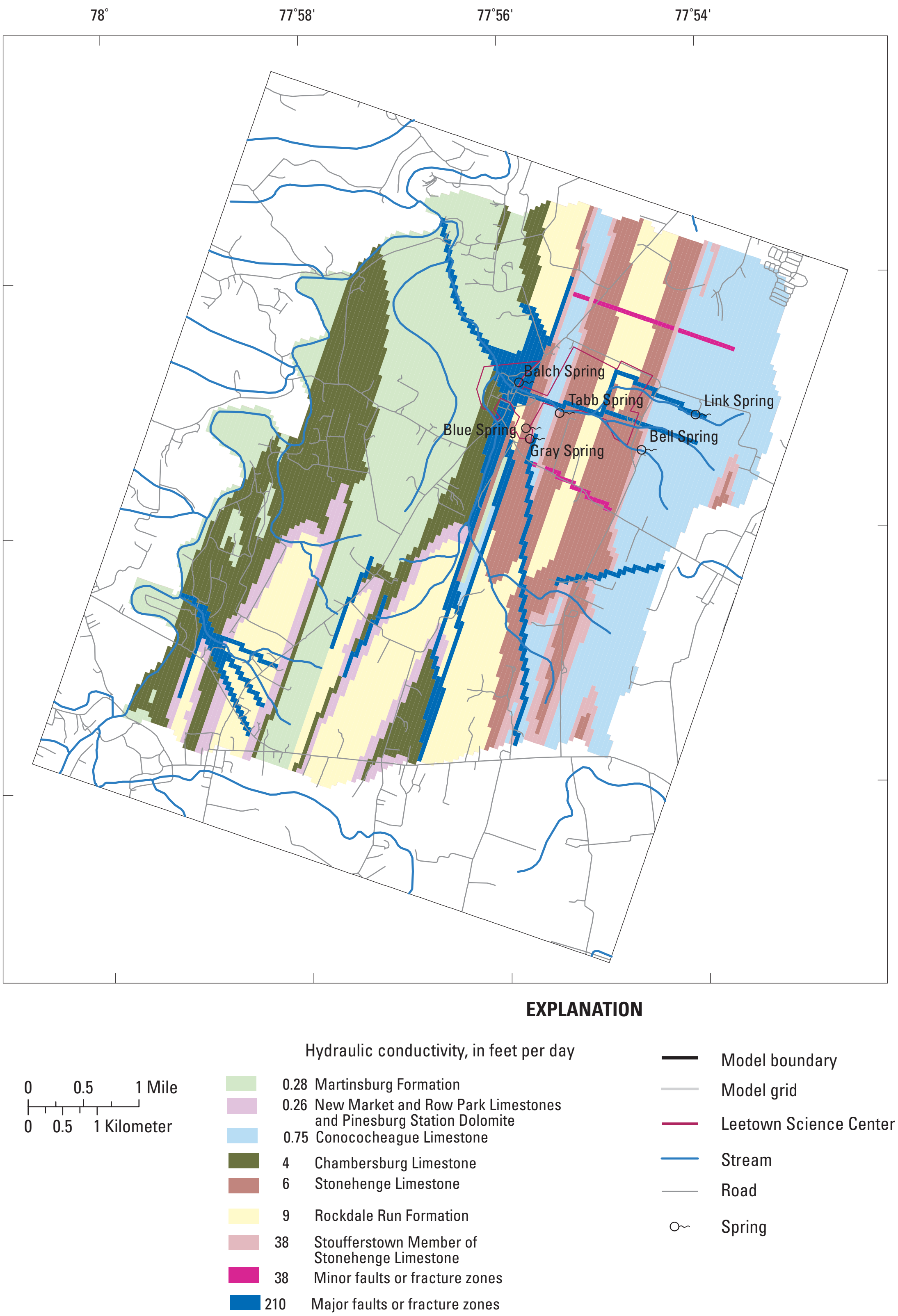


Figure 9. Hydraulic conductivity assigned to geologic formations, faults, and fracture zones in the middle layer of the ground-water flow model of the Leetown area, West Virginia.

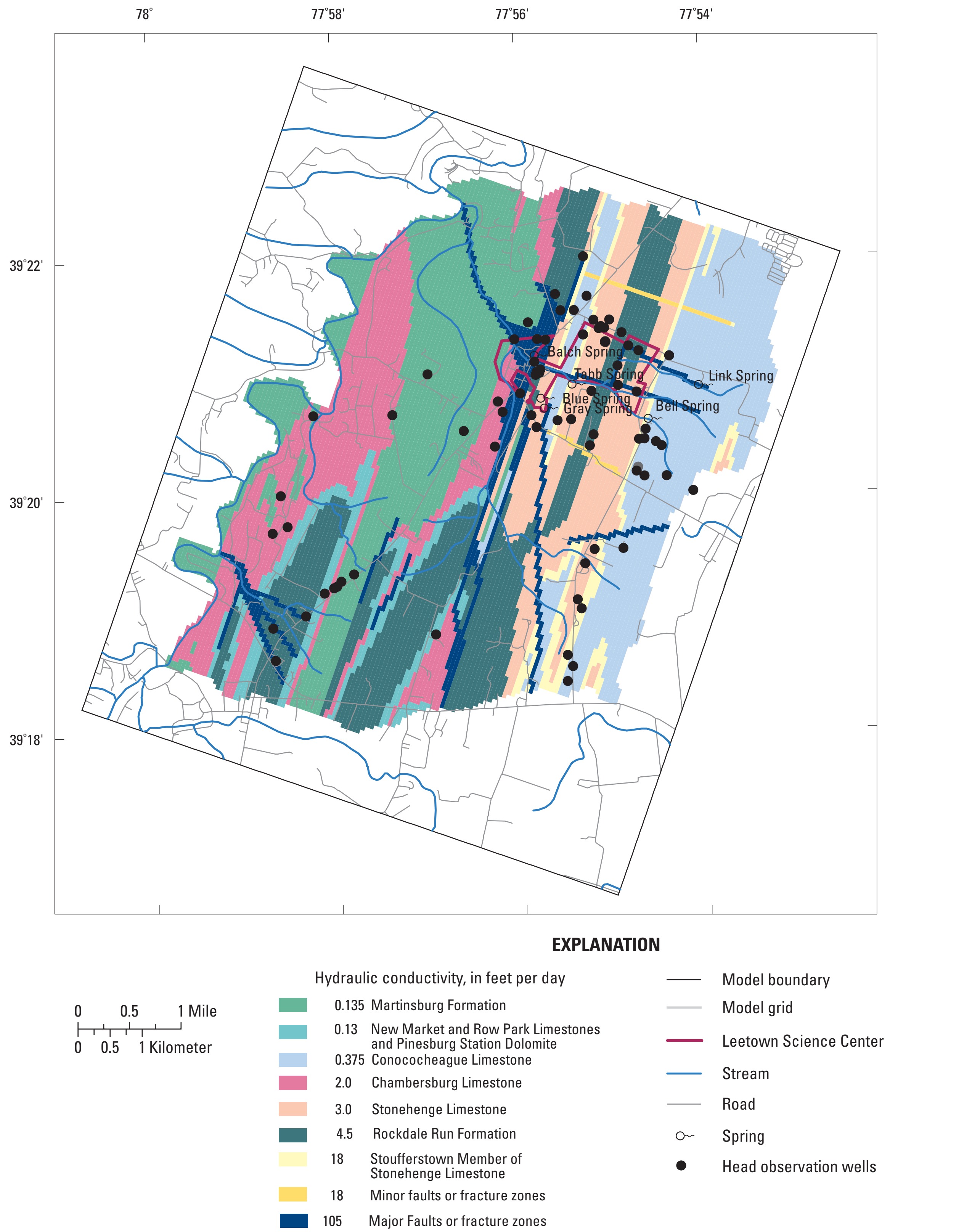


Figure 10. Hydraulic conductivity assigned to geologic formations, faults, and fracture zones in the bottom layer of the ground-water flow model of the Leetown area, West Virginia

Table 6. Total monthly streamflow, ground-water discharge, and surface runoff for the Hopewell Run watershed at the Leetown streamflow-gaging station, West Virginia.

[in., inches; ft^3/s, cubic feet per second]

Date	Measured streamflow (ft^3/s)	Total streamflow[10] (ft^3/s)	Total streamflow[10] (in.)	Ground-water discharge[10] (in.)	Surface runoff[10] (in.)
Apr-03	584	617.42	2.57	2.44	0.13
May-03	598	632.53	2.63	2.46	0.17
Jun-03	784	817.42	3.40	3.06	0.33
Jul-03	433.8	468.33	1.95	1.94	0.01
Aug-03	262.4	296.93	1.23	1.14	0.09
Sep-03	323.1	356.52	1.48	1.32	0.17
Oct-03	307.7	342.23	1.42	1.37	0.06
Nov-03	349	382.42	1.59	1.51	0.08
Dec-03	623	657.53	2.73	2.42	0.32
Jan-04	396	430.53	1.79	1.78	0.01
Feb-04	570.8	603.11	2.51	2.25	0.25
Mar-04	453	487.53	2.03	2.00	0.02
Apr-04	626	659.42	2.74	2.41	0.33
May-04	488	522.53	2.17	2.10	0.07
Jun-04	397.9	431.32	1.79	1.64	0.15
Jul-04	276.6	311.13	1.29	1.21	0.08
Aug-04	251.7	286.23	1.19	1.09	0.1
Sep-04	286.6	320.02	1.33	1.08	0.25
Oct-04	280.2	314.73	1.31	1.27	0.03
Nov-04	249.4	282.82	1.18	1.08	0.09
Dec-04	382.1	416.63	1.73	1.64	0.09
Jan-05	320.7	355.23	1.48	1.45	0.02
Feb-05	241.8	272.99	1.13	1.11	0.02
Mar-05	427.1	461.63	1.92	1.61	0.31
Apr-05	608	641.42	2.67	2.51	0.16
May-05	304.9	339.43	1.41	1.38	0.03
Jun-05	180.3	213.72	0.89	0.85	0.04
Jul-05	140.9	175.43	0.73	0.65	0.07
Aug-05	119.9	154.43	0.64	0.58	0.06
Sep-05	96.1	129.52	0.54	0.46	0.08

Table 6. Total monthly streamflow, ground-water discharge, and surface runoff for the Hopewell Run watershed at the Leetown streamflow-gaging station, West Virginia.—Continued

[in., inches; ft^3/s, cubic feet per second]

Date	Measured streamflow (ft^3/s)	Total streamflow[10] (ft^3/s)	Total streamflow[10] (in.)	Ground-water discharge[10] (in.)	Surface runoff[10] (in.)
Oct-05	101.7	136.23	0.57	0.46	0.11
Nov-05	108.2	141.62	0.59	0.50	0.09
Dec-05	140.5	175.03	0.73	0.70	0.03
Jan-06	208.4	242.93	1.01	0.94	0.07
Feb-06	178.6	209.79	0.87	0.85	0.02
Mar-06	154	188.53	0.78	0.77	0.01

[10]Streamflow data in this table includes all discharge for the basin and the Center at the gage including corrections for a 500 gal/min diversion to a pond.

Center (app. 4) and at the nearby Martinsburg airport (table 1). The major output, stream discharge from Hopewell Run, was measured at the gaging station just downstream from the Center. The only components of the water budget that were not measured directly were evaporation and transpiration. These components were estimated by subtracting the total measured streamflow from recorded precipitation totals.

The water budget can be expressed by the equation
$P = SRO + GWD + ET \pm \delta S$,
where P is the total precipitation, SRO is the component of streamflow that occurs as a result of surface runoff, GWD is the ground-water discharge to the stream (stream baseflow), ET is evapotranspiration, and δS is the change in ground-water storage. Changes in storage (δS) were computed by comparing the difference in mean discharge between the beginning and ending periods of the water year and averaging the difference over the 8.95 mi^2 drainage basin. As streamflow decreased over the two year period, the average change in storage was -4.72 in/yr. Therefore, the only unmeasured quantity was ET, which was estimated by difference. Given an average measured precipitation of 38.60 in/yr over the 2-year period, total measured streamflow of 19.09 in/yr (surface runoff of 1.36 in/yr and ground-water discharge of 17.73 in/yr) based on hydrograph-separation techniques, the water budget equation was rearranged to solve for ET by filling in the known terms:

$$ET = P - (SRO + GWD \pm \delta S)$$

$$ET = 38.60 - (1.36 + 17.73 - 4.72) = 24.23 \text{ in/yr}$$

Once ET has been estimated, the complete water budget equation can then be written as

$$P = SRO + GWD + ET \pm \delta S$$

$$38.60 = 1.36 + 17.73 + 24.23 - 4.72$$

with all terms expressed in inches per year.

The average precipitation for the two-year period at the Martinsburg airport of 38.60 in/yr and base-flow discharge estimated by hydrograph separation of stream-flow (Rutledge, 1998) data from Hopewell Run of 17.73 in/yr compare favorably to the long-term average precipitation for the Martinsburg airport of 39.39 in/yr and recharge of 16.5 in/yr estimated by hydrograph analysis of stream-flow data for Hopewell Run using Rorabaugh methods (Rutledge, 1998). The minor difference in recharge estimated with the two techniques may be attributed to the relatively minor amounts of water lost to riparian evapotranspiration and (or) to subtle differences in mathematical analyses and computations used in the two methods. Estimated input recharge to the ground-water flow model was set at 16.5 in/yr. Also, based on hydrograph separation of daily streamflow data for the Hopewell Run gaging station (April 2003 through March 2006), approximately 93 percent of water in Hopewell Run is estimated to be derived from ground water discharge and only 7 percent is surface runoff.

Ground-Water Flow Directions

Ground-water flow was analyzed by examining the head equipotentials in the upper layer of the model (fig. 12). Surface and ground-water flow over half the modeled area, including the Hopewell Run watershed, flows through the Leetown area. Generally, ground-water flows from topographically high areas toward Hopewell Run. Large quantities of surface and ground water are funneled through a relatively narrow gap in the

Table 7a. Results of sensitivity analyses showing effects of varying hydraulic conductivity during development and calibration of a ground-water flow model of the Leetown area, West Virginia .

[ft, feet; ft/d, feet per day; in/yr, inches per year; RMS, root mean square; numbers in bold type indicate the parameter varied during the sensitivity analysis]

	Calibrated					Sensitivity tests			
Geologic formation	Hydraulic conductivity (ft/d)	Hydraulic conductivity (ft/d)	RMS error[11] (ft)	Normalized RMS error[11] (percent)	Correlation[11] coefficient	Hydraulic conductivity (ft/d)	RMS error (ft)	Normalized RMS error (percent)	Correlation coefficient
Major faults or Fracture Zones	420	**280**	5.66	3.57	0.989	**560**	6.28	3.96	0.988
	210	**140**				**280**			
	105	**70**				**140**			
Martinsburg Formation	0.35	**0.2**	5.67	3.57	0.984	**0.4**	5.03	3.17	0.988
	0.275	**0.17**				**0.34**			
	0.135	**0.08**				**0.17**			
Chambersburg Limestone	8	**5.4**	5.02	3.17	0.989	**10.6**	4.9	3.09	0.988
	4	**2.7**				**5.3**			
	2	**1.34**				**2.65**			
New Market and Row Park Limestones and Pinesburg Station Dolomite	0.32	**0.21**	5.02	3.17	0.988	**0.42**	5.05	3.19	0.988
	0.26	**0.17**				**0.34**			
	0.13	**0.09**				**0.17**			

Table 7a. Results of sensitivity analyses showing effects of varying hydraulic conductivity during development and calibration of a ground-water flow model of the Leetown area, West Virginia—Continued.

[ft, feet; ft/d, feet per day; in/yr, inches per year; RMS, root mean square; numbers in bold type indicate the parameter varied during the sensitivity analysis]

	Calibrated	Calibrated	Calibrated	Calibrated	Calibrated	Sensitivity tests	Sensitivity tests	Sensitivity tests	Sensitivity tests
Geologic formation	Hydraulic conductivity (ft/d)	Hydraulic conductivity (ft/d)	RMS error[11] (ft)	Normalized RMS error[11] (percent)	Correlation[11] coefficient	Hydraulic conductivity (ft/d)	RMS error (ft)	Normalized RMS error (percent)	Correlation coefficient
Rockdale Run Formation	18	**12**	4.7	2.97	0.99	**24**	4.79	3.03	0.989
	9	**6**				**12**			
	4.5	**3**				**6**			
Stonehenge Limestone	12	**8**	4.92	3.11	0.989	**16**	4.95	3.13	0.989
	6	**4**				**8**			
	3	**2**				**4**			
Stoufferstown Member of Stonehenge Limestone and minor faults/fracture zones	76	**54**	4.81	3.04	0.989	**98**	4.72	2.98	0.99
	38	**27**				**49**			
	18	**13.5**				**22.5**			
Conococheague Limestone	1.5	**0.8**	6.24	3.94	0.984	**1.6**	5.12	3.23	0.989
	0.75	**0.4**				**0.8**			
	0.375	**0.2**				**0.4**			

[11]The calibrated ground-water flow model had a root mean square error of 4.59 ft, a normalized root mean square error of 2.90 percent, and a correlation coefficient of 0.99.

Table 7b. Results of sensitivity analyses showing effects of varying recharge, vertical hydraulic conductivity, and anisotropy during development and calibration of a ground-water flow model of the Leetown area, West Virginia.

[ft, feet; ft/d, feet per day; in/yr, inches per year; RMS, root mean square; numbers in bold type indicate calibrated parameters input during the sensitivity analyses]

Parameter	Input value	RMS error (ft)	Normalized RMS error (percent)	Correlation coefficient
Recharge	13	9.26	5.85	0.989
	16.5	**4.60**	**2.90**	**0.99**
	20	6.86	4.34	0.988
Vertical hydraulic conductivity	5:1	4.75	3.00	0.989
	10:1	**4.60**	**2.90**	**0.99**
	15:1	4.83	3.05	0.989
Anisotropy	4:1	8.05	5.08	0.984
	2:1	**4.60**	**2.90**	**0.99**
	1:1	6.24	3.94	0.987

Table 7c. Results of sensitivity analyses showing the effects of varying effective porosity during development and calibration of a ground-water flow model of the Leetown area, West Virginia.

[ft/d, feet per day]

Effective porosity (percent)	Ground-water[12] velocity (ft/d)
Calibrated	
1.0	40-120
Simulated	
0.25	60-210
4.0	8-37

[12]Ground-water flow velocity sensitivity analysis was conducted only for the simulated conduit drains.

eastern portion of Center property where Hopewell Run cuts through the Martinsburg Formation (fig. 2). The lower hydraulic conductivity of the Martinsburg Formation (figs. 8, 9, and 10) plays an integral role in this “funneling” effect by creating a hydraulic boundary that acts like a dam and retards westward flow of both surface and ground water. Water is forced to travel roughly parallel to bedrock strike along a series of thrust faults (fig. 2) that parallel the Martinsburg Formation and act as drains conveying water northward toward Leetown and the Center. These complex geologic features are responsible for the large springs (Blue, Gray, and Balch Springs) at the Center (fig. 9). Consequently, the Center is uniquely situated with respect to both ground- and surface-water resources.

Ground-water flow directions in the northern part of the model area near Kearneysville (near the 475- and 485-ft head equipotential lines on fig. 12) are difficult to determine primarily as a result of very flat topography, vague or poorly defined surface-water divides, and karst topography. Surface topography seems to indicate flow toward the south, but a fracture zone in this area may also convey ground-water westward through a gap in the Martinsburg Formation. Such vague watershed boundaries are common in karst terrains. Similar vague but less pronounced surface- and ground-water divides occur near Johnsontown to the east and Harewood to the south.

The vague surface and ground-water divides in the Kearneysville area affect the delineation of the recharge area to Balch Spring, which depends on analysis of ground-water flow directions implied by dye-tracer tests, head equipotentials, and geologic structure. The probable recharge areas to the Blue and Gray Spring complex and Balch Spring are shown in figure 13. Best available hydrogeologic data and results of the current ground-water flow simulation indicate a primary recharge area for Balch Spring to the east and north and a recharge area for the Blue and Gray Spring complex to the south and east (fig. 13). While the recharge areas delineated and shown on figure 13 indicate distinct areas of recharge to specific springs, results of dye tracer tests conducted in the Leetown area (Jones, 1997: Jones and Deike, 1981) show significant overlap in the recharge areas to the Center’s primary springs. The recharge areas shown in figure 13 should be viewed as approximate, as the recharge areas are likely different under differing hydrologic conditions; such as high ground-water level conditions when epikarst feature are dominant and low ground-water level conditions when ground-water flow in diffuse fractures is dominant.

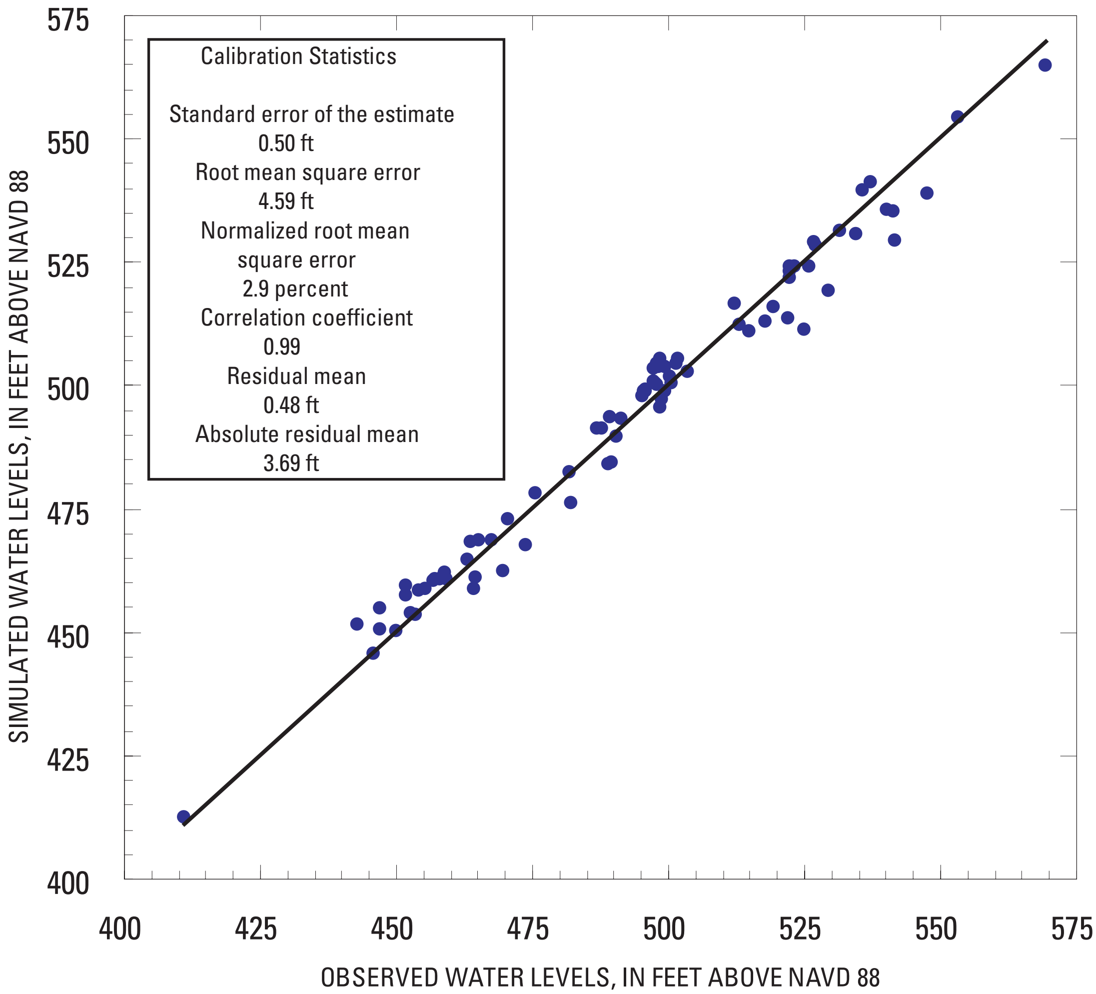


Figure 11. Relation between simulated and observed water levels in 83 observation wells in the Leetown area, West Virginia.

Particle tracking analyses were made using the MODPATH (Pollock, 1998) subroutine within Visual MODFLOW to estimate potential flow velocities in the upper layer of the ground-water flow model. Flow-velocity estimates for the simulated conduit drains ranged from 40 to 120 ft/d, similar to the 20- to 100-ft/d velocities obtained from dye tracer tests conducted for this investigation. Estimated flow velocities for the more permeable limestone formations ranged from 1.2 to 4.4 ft/d, but the less permeable Conococheague Limestone and the Martinsburg Formation yielded flow velocity estimates of 0.7 to 0.9 ft/d and 0.3 to 0.5 ft/d, respectively. Flow in the deeper bedrock formations would be even slower.

Simulation of Varying Withdrawals and Climatic Conditions

Currently, the Center obtains water for operations from Blue, Gray, and Balch Springs (fig. 14) and from three production wells (sites 84-86 in figure 14a). In addition, four potential production wells (sites 87-90 in figure 8) were installed for possible expansion of operations at the USGS Leetown Science Center, including the co-located USDA NCCWA facility. Various withdrawal scenarios were simulated to determine the effects of present operations on water availability and to predict the potential effects of an anticipated additional 150 to 200-gal/min withdrawal of water to expand operations at the facilities. Scenarios simulated included (1) withdrawals at current levels, (2) withdrawing an additional 50 gal/min from well 87 and 100 gal/min from well 88 (two new production wells recently installed at the Center), (3) withdrawing 75 and 100 gal/min respectively, from wells 87 and 88, (4) withdrawing 100 gal/min each from the two new production wells, and (5) withdrawals from two hypothetical subdivision wells.

The simulations included an analysis of both the effects of withdrawals from production wells on water levels and the net effect of withdrawals on the streamflow of Hopewell Run. The probable maximum yield of wells, median discharge of springs, and current annual median ground-water withdrawal rates from

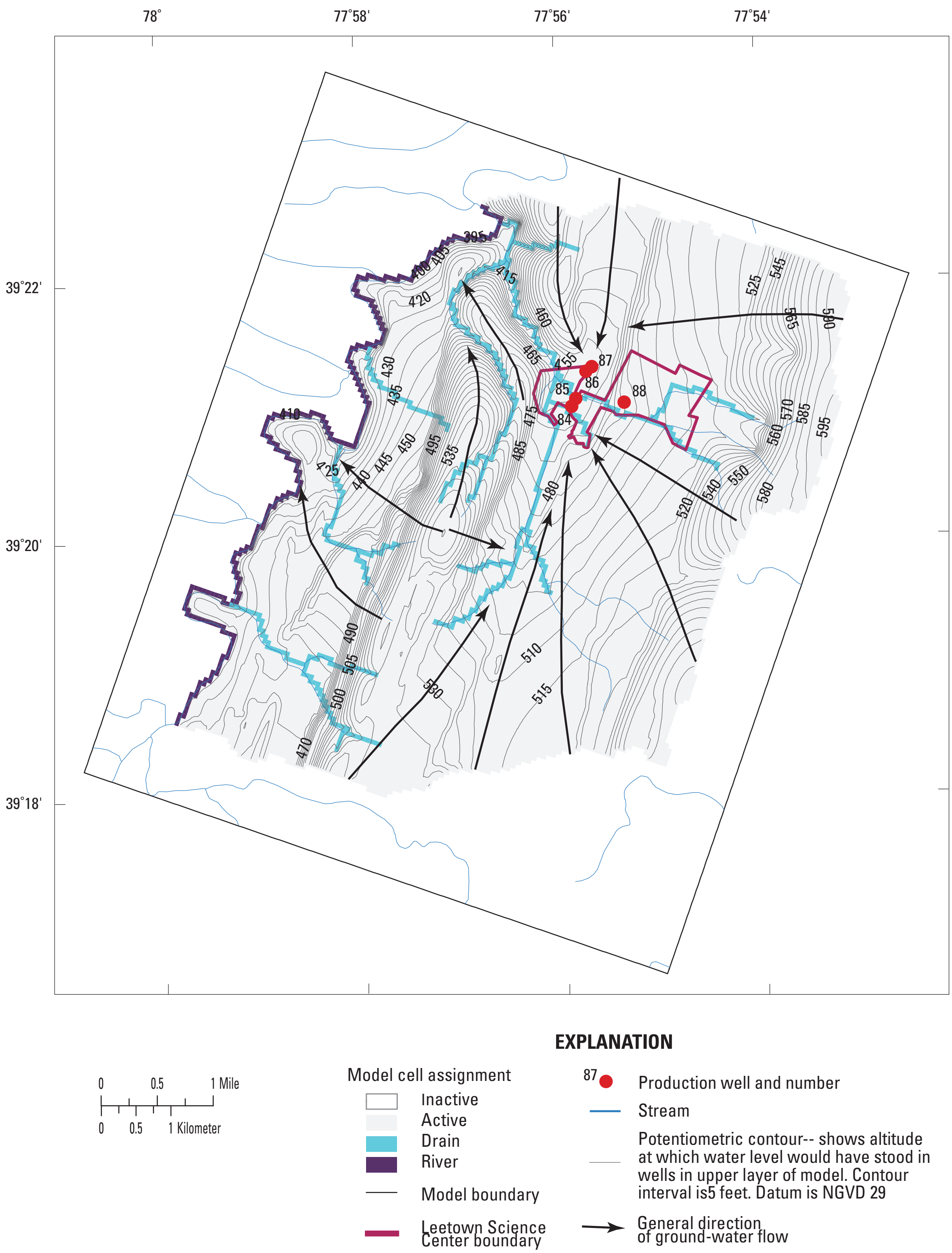


Figure 12. Simulated potentiometric-surface contours in the upper layer of the ground-water flow model of the Leetown area, West Virginia under normal climatic conditions.

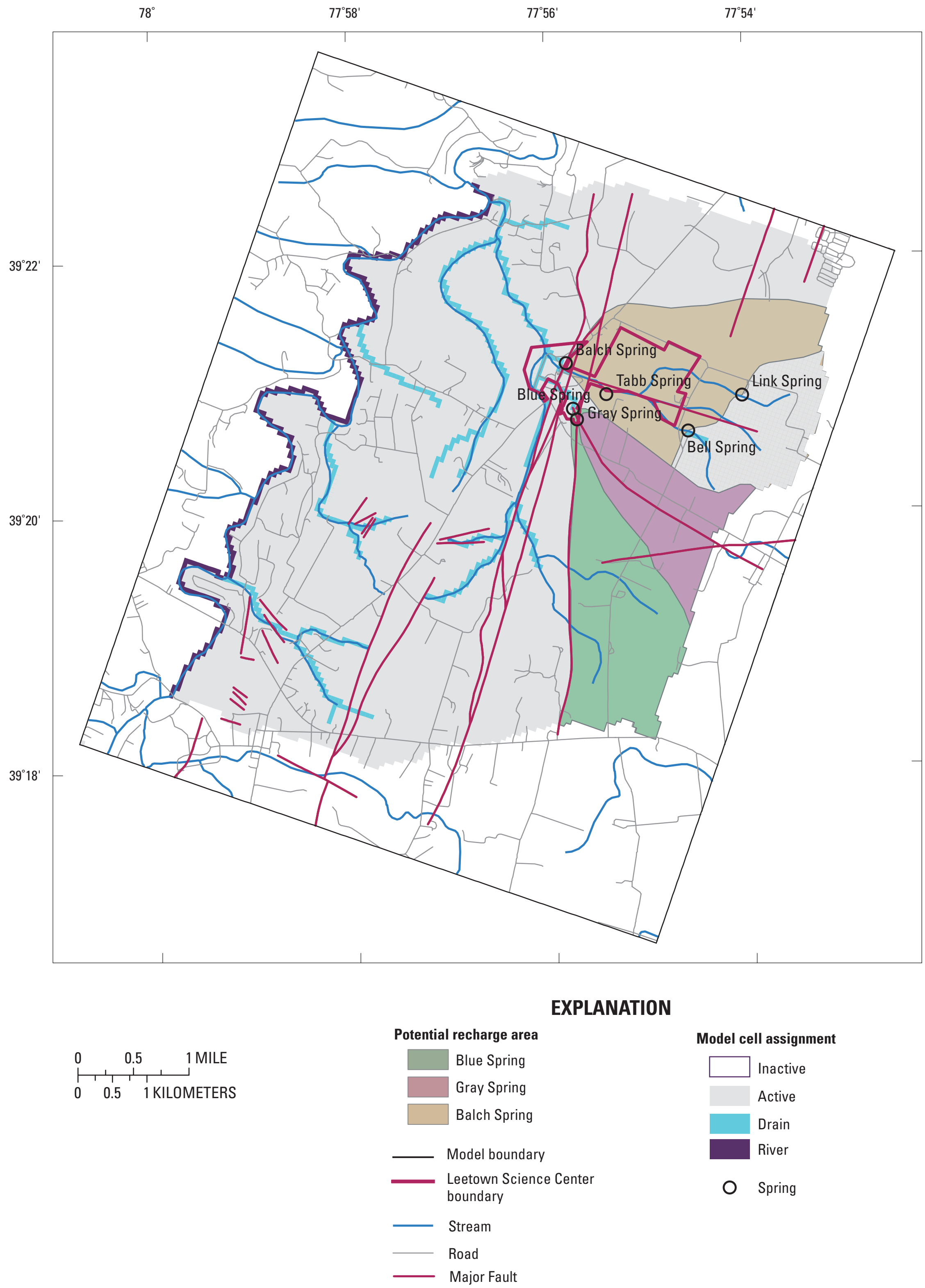


Figure 13. Simulated potential recharge areas to major springs in the Leetown area, West Virginia.

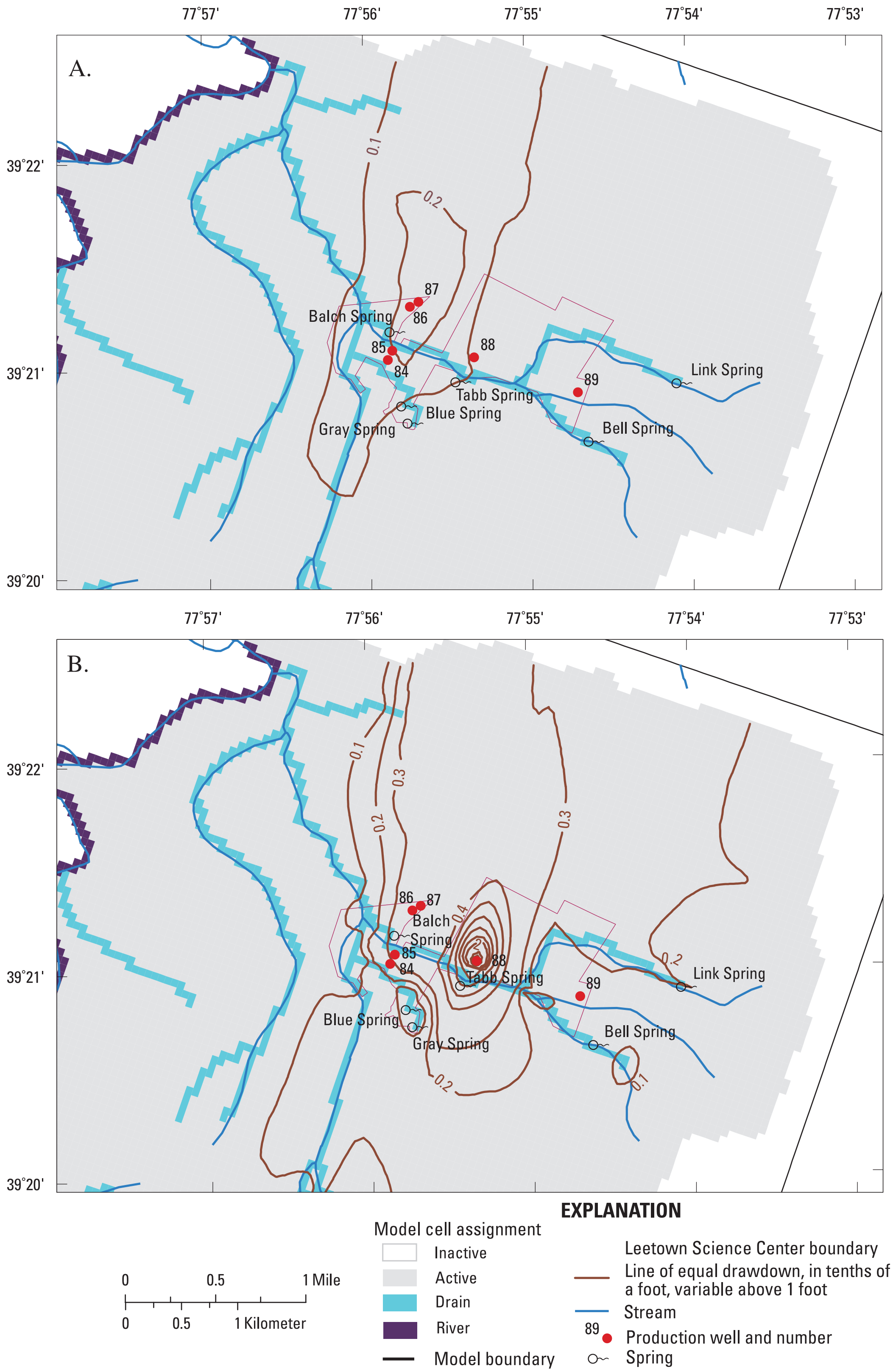


Figure 14. Simulated drawdown in the Leetown area, West Virginia, (A) under existing pumping conditions during normal climatic conditions, and (B) resulting from the addition of production wells 87 and 88 pumping at 50 and 100 gallons per minute during normal climatic conditions.

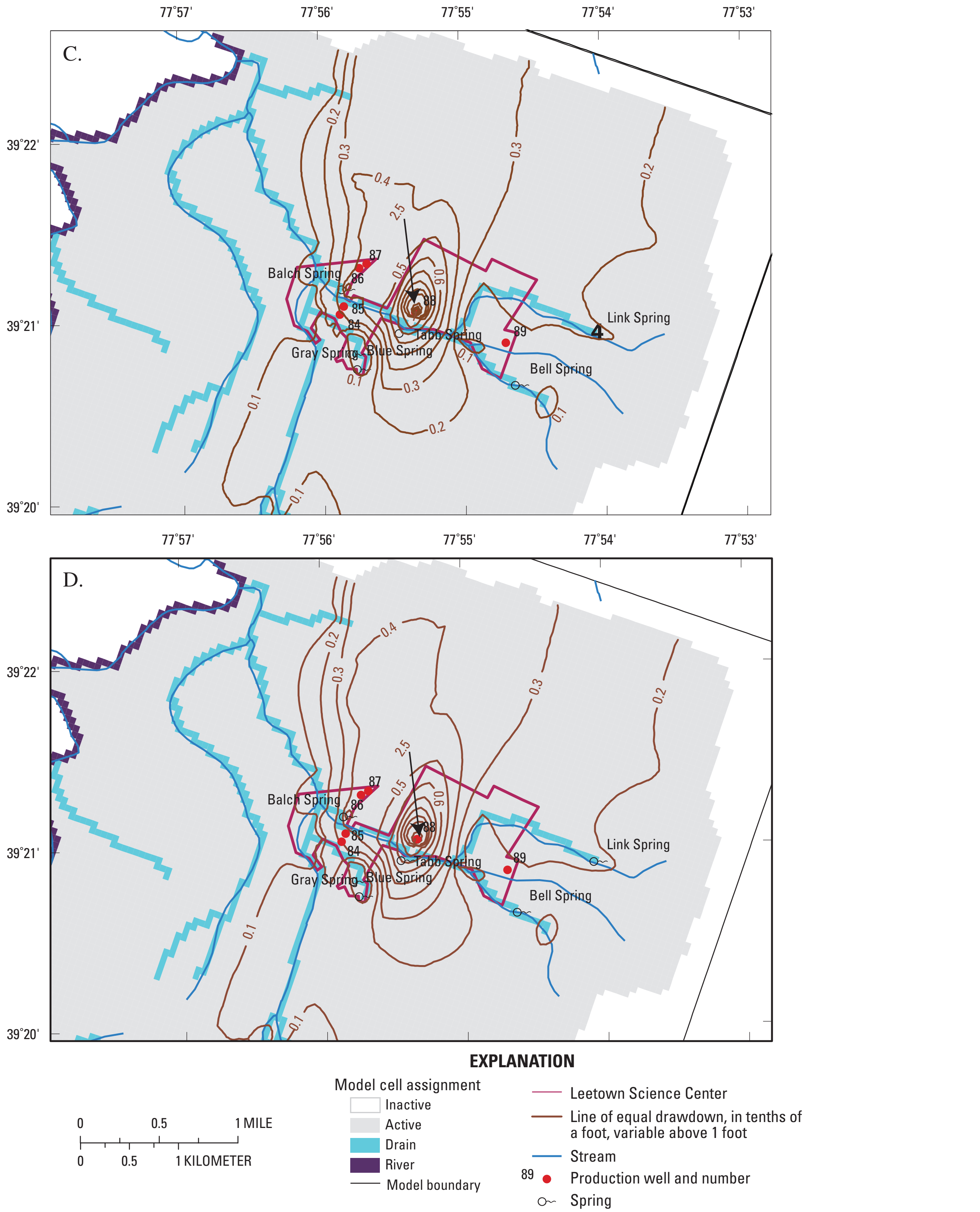


Figure 14. Simulated drawdown in the Leetown area, West Virginia, (C) resulting from the addition of production wells 87 and 88 pumping at 75 and 100 gallons per minute during normal climatic conditions, and (D) resulting from the addition of production wells 87 and 88 pumping at 100 gallons per minute each during normal climatic conditions.

wells and springs at the Center are shown in table 4.

The withdrawals of water from the Center's production wells and Balch Spring were simulated as pumped wells in the model. Flow from the Blue and Gray Spring complex occurs primarily under gravity-flow and these springs were simulated as drain nodes in the model. Pumping rates used in the model were based on the data presented in table 4.

Simulated Drawdown Near Springs and Existing and Proposed Wells

In the first scenario, current withdrawal rates of 100 and 80 gal/min from production wells A and B respectively (sites 84 and 85 in figure 12), for a typical 3-month period in late summer to early fall and an average withdrawal of 190 gal/min from Balch Spring were simulated. The ground-water flow model was run first under non-pumping conditions and subsequently under current normal pumping conditions at the Center and future anticipated withdrawal rates to assess the effect of current and future withdrawals on the hydrology of the area. Initial scenarios were made based on long-term average recharge for the basin. The drawdown induced by the current pumping scheme is minimal, less than 0.10 ft near Blue and Gray Springs and approximately 0.10 to 0.20 ft near Balch Spring (fig. 14A). The corresponding effect on streamflow is also minimal, with a simulated reduction in streamflow of 0.51 ft^3/s, or 4.7 percent of streamflow under non-pumping conditions (table 8). The potential reductions of streamflow is primarily a result of capture of ground water that would have discharged to streams in the absence of pumping; however, some loss of streamflow directly to ground water is also possible. A loss of approximately 0.87 and 0.35 ft^3/s of water across a fault at the Center at two locations was documented by means of seepage measurements made during the course of this investigation.

For the second scenario, increasing current withdrawals by pumping from two new production wells at rates of 50 (well 87 in figure 12) and 100 gal/min (well 88 in figure 12) produces a simulated decrease in streamflow of 0.83 ft^3/s or 7.7 percent compared to non-pumping conditions (table 8). This reduction in streamflow affects only a small reach of stream immediately adjacent to the Center. Also, this effect results from a temporary diversion of water rather than consumptive use, as most of the water is returned to the stream after use just upstream from the confluence of the East and South Branches of Hopewell Run. Therefore, the reduction in the flow of Hopewell Run downstream from the Center would be minimal, caused only by evaporation of water used for research operations at the facility. Simulated water-level drawdown (over non-pumping conditions) resulting from the additional 150 gal/min withdrawal is approximately 0.30 to 0.40 ft near Balch Spring and approximately 0.10 ft in the vicinity of Blue and Gray Springs (fig. 14 B). Although drawdown of 0.5 ft under normal conditions may seem small, the effect on spring flow could be substantial, especially at lower flow regimes and during droughts. As the springs are the primary source of water to the Center, a pumping schedule that reduces the effect of ground-water withdrawals to existing spring flows is preferred. Balch Spring appears to be especially susceptible to reduction in flow as a result of pumping wells for additional water. The low hydraulic conductivity (figs. 8, 9, and 10) of the Conococheauge Limestone (fig. 2) acts as a barrier to ground-water flow and may isolate the flow of Balch, Blue, and Gray Springs from the effects of withdrawals from well 88 (fig. 12) under normal climatic conditions. Withdrawal of a larger volume of water from well 88 and a corresponding smaller volume of water from well 87 appears to reduce the effect of additional withdrawals on the Center's existing springs and production wells.

In the third scenario, withdrawals of 100 gal/min from well 88 and 75 gal/min from well 87 (fig. 14C), rather than the 150-gal/min additional withdrawal simulated in scenario 2, were added to current withdrawals. The overall effect on net streamflow (table 8) of the 175-gal/min withdrawal is similar to the 150-gal/min withdrawal simulated to augment existing supplies. Drawdown (over non-pumping conditions) induced by current pumping with the additional 175 gal/min withdrawal is approximately 0.50 ft near Balch Spring and 0.10 ft near Blue and Gray Springs. A corresponding reduction in streamflow (over non-pumping conditions) of 0.88 ft^3/s, or about 8.1 percent (table 8) results from additional withdrawals from the new production wells at a combined rate of 175 gal/min to augment current supplies.

Finally, simulated drawdown of 0.5 ft in the vicinity of Balch Spring and 0.1 ft in the vicinity of Blue and Gray Springs occurs when each of the two new production wells is pumped at 100 gal/min to augment existing supplies (fig. 14D). A corresponding reduction in streamflow (over non-pumping conditions) of 0.93 ft^3/s or about 8.6 percent is predicted (table 8), with simulated withdrawals of 200 gal/min augmenting current supplies. Thus, even with additional withdrawals of approximately 200 gal/min; total diversion of streamflow is predicted to be less than 9 percent during slightly above- normal hydrologic conditions similar to those for which the ground-water flow model was developed and calibrated.

Additional simulations were conducted at recharge rates between those used to develop the model and that used to simulate the 1999 drought to provide a benchmark against which future withdrawals can be assessed. These added scenarios were based on (1) non-pumping conditions and on (2) current demands with additional withdrawals of 150 gal/min at recharge rates of 10.37, 12.41, and 14.46 in/yr (table 8).

Streamflow at the Hopewell Run gaging for the 3-year period of record was correlated with the long-term record available for the Opequon Creek at Martinsburg (table 9). The methods used are outlined by Wiley (2006) who analyzed long-term streamflow records in West Virginia for the period 1930-2002. The correlation was made to assess potential streamflow as a function of ground-water withdrawals and model predictions.

Table 8. Changes in simulated streamflow at the Hopewell Run streamflow-gaging station for current and anticipated withdrawals of ground water from production wells in the Leetown area, West Virginia.

[ft^3/s, cubic feet per second; ft^3/d, cubic feet per day; gal/min, gallons per minute; in/yr, inches per year; na, not applicable]

Ground-water withdrawals	Simulated recharge rate (in/yr)	Simulated streamflow (ft^3/d)	Streamflow (ft^3/s)	Percent change from nonpumping conditions
Ambient flow (no pumping)	16.5	935,530	10.83	na
Wells #84, #85, #86, and Balch Spring	16.5	891,370	10.32	-4.7
Wells #84, #85, #86, Balch Spring, and new 50 and 100 gal/min production wells	16.5	864,150	10.00	-7.7
Wells #84, #85, #86, Balch Spring, and new 75 and 100 gal/min production wells	16.5	859,810	9.95	-8.1
Wells #84, #85, #86, Balch Spring, and two new 100 gal/min production wells	16.5	855,460	9.90	-8.6
Wells #84, #85, #86, Balch Spring, two new 100 gal/min production wells, and two subdivision wells pumping at a combined rate of 117 gal/min	16.5	833,470	9.65	-10.9
Ambient flow (no pumping)	14.46	767,930	8.89	na
Wells #84, #85, #86, Balch Spring, and new 50 and 100 gal/min production wells	14.46	697,430	8.07	-9.2
Ambient flow (no pumping)	12.41	603,500	6.98	na
Wells #84, #85, #86, Balch Spring, and new 50 and 100 gal/min production wells	12.41	534,494	6.19	-11.4
Ambient flow (no pumping)	10.37	445,014	5.15	na
Wells #84, #85, #86, Balch Spring, and new 50 and 100 gal/min production wells	10.37	378,578	4.38	-14.9
Ambient flow (no pumping)	8.32	290,081	3.36	na
Wells #84, #85, #86, and Balch Spring	8.32	250,769	2.90	-13.7
Wells #84, #85, #86, Balch Spring, and new 50 and 100 gal/min production wells	8.32	227,680	2.64	-21.4
Wells #84, #85, #86, Balch Spring, and new 75 and 100 gal/min production wells	8.32	224,090	2.59	-22.9
Wells #84, #85, #86, Balch Spring, and two new 100 gal/min production wells	8.32	220,300	2.55	-24.1
Wells #84, #85, #86, Balch Spring, two new 100 gal/min production wells, and two subdivision wells pumping at a combined rate of 117 gal/min	8.32	203,210	2.35	-30.0

Simulated flow in Hopewell Run at Leetown for the 1999 drought was approximately 3.40 ft^3/s (table 8) and is approximately equal to the 83-percent streamflow duration (table 9). The corresponding median measured flows for the Opequon Creek at Martinsburg in the 1999 water year was 74.0 ft^3/s, and is approximately equal to the 80-percent long-term flow duration for the Opequon Creek. Thus, based on the correlation with the streamflow in the Opequon Creek at Martinsburg, the simulated long-term steady-state flow of 3.40 ft^3/s simulated for the 1999 drought for the Hopewell Run watershed is reasonable. An estimate of the 7-day, 10-year low-flow statistic for Hopewell Run at Leetown is 1.75 ft^3/s. The 7-day, 10-year low-flow

Table 9. Flow-duration statistics for the Opequon Creek at Martinsburg streamflow-gaging station and estimated flow-duration statistics for the Hopewell Run at Leetown streamflow-gaging station, West Virginia.

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

Flow-duration statistic	Flow-duration statistics for Opequon Creek at Martinsburg (ft^3/s)	Estimated flow-duration statistic for Hopewell Run at Leetown (ft^3/s)
1-day 2-year hydrological-based flow[13]	50.6	2.52
1-day 5-year hydrological-based flow	38.4	1.88
1-day 10-year hydrological-based flow	33.5	1.63
3-day 2-year hydrological-based flow	51.7	2.57
3-day 5-year hydrological-based flow	39.4	1.94
3-day 10-year hydrological-based flow	34.5	1.68
7-day 2-year hydrological-based flow	53.6	2.67
7-day 5-year hydrological-based flow	40.8	2.01
7-day 10-year hydrological-based flow [13]	35.8	1.75
14-day 2-year hydrological-based flow	55.9	2.79
14-day 5-year hydrological-based flow	42.4	2.09
14-day 10-year hydrological-based flow	37.1	1.82
30-day 2-year hydrological-based flow	61.1	3.07
30-day 5-year hydrological-based flow	46.0	2.28
30-day 10-year hydrological-based flow	40.0	1.97
1-day 3-year biological-based flow[14]	32.0	1.56
4-day 3-year biological-based flow	33.9	1.65
EPA harmonic-mean flow	115	5.95
25-percent duration flow[15]	256	13.8
30-percent duration flow	224	12.0
35-percent duration flow	198	10.5
40-percent duration flow	176	9.29
45-percent duration flow	157	8.24
50-percent duration flow	140	7.31
55-percent duration flow	125	6.49
60-percent duration flow	113	5.84
65-percent duration flow	101	5.19
70-percent duration flow	91.2	4.67
75-percent duration flow	82.4	4.19
80-percent duration flow	73.9	3.74

Table 9. Flow-duration statistics for the Opequon Creek at Martinsburg streamflow-gaging station and estimated flow-duration statistics for the Hopewell Run at Leetown streamflow-gaging station, West Virginia.—Continued

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

Flow-duration statistic	Flow-duration statistics for Opequon Creek at Martinsburg (ft^3/s)	Estimated flow-duration statistic for Hopewell Run at Leetown (ft^3/s)
85-percent duration flow	65.5	3.30
90-percent duration flow	57.5	2.88
95-percent duration flow	49.0	2.43
99-percent duration flow	37.5	1.84

[13]Hydrological-based flow is a low-flow statistic based on consecutive days of streamflow discharge over a specified period of time. For example, the 7-day 10-year hydrological-based flow (7Q10) is the lowest 7-day flow which occurs on average over a 10-year period.

[14]The 1-day 3-year biological-based flow is the lowest daily discharge on average over a 3-year period that can sustain aquatic life.

[15]The 25-percent duration flow is the discharge that is expected to be exceeded only 25 percent of the time on average; that is, 75% of the time the streamflow discharge is expected be less than the flow-duration discharge.

statistic is a common reference used by regulatory agencies for minimum in stream flows. The higher flow-duration statistics (those greater than the 50-percent flow duration) are less accurate and likely are biased high due to a poor correlation between peak discharge in the two basins as a function of drainage area (Hopewell Run, 8.95 mi^2; Opequon Creek, 273 mi^2). However, the base-flow estimates such as the 7-day, 10-year low flow and the estimates made for the 1999 drought in the Hopewell run watershed are much more accurate.

Simulated Effects of Drought

In order to assess the potential effect of drought on water availability in the Leetown area, recharge in the model was reduced from a long-term average rate of 16.5 in/yr to 8.32 in/yr. This value represents conditions similar to those in 1999, when the region experienced the most severe drought on record with respect to duration and the fifth most severe drought on record with respect to lack of precipitation. Simulated water levels and streamflow under normal conditions (fig. 12 and table 8) were compared to water levels and streamflow simulated for drought conditions (fig. 15 and table 8). Simulated water levels are approximately 10 to 15 ft lower in lowland areas and approximately 40 to 55 ft lower in upland areas during drought conditions (fig. 15) than during normal conditions (fig. 12).

Drawdown is also substantially greater under drought conditions (fig. 16 A-D) than under normal conditions (fig. 14 A-D). Under drought conditions and current withdrawal demands, drawdown (compared to non-pumping conditions) of 0.70 ft near Balch Spring and 0.30 to 0.40 ft near Blue and Gray Springs are predicted (fig. 16A). A corresponding reduction in streamflow (over non-pumping conditions) during a simulated drought of 0.46 ft^3/s, or 13.7 percent is predicted (table 8) based on current demands.

Effects of drought also were evaluated for current pumping conditions augmented by new 50 and 100 gal/min production wells. Total drawdown of approximately 1.0 ft near Balch Spring and 0.30 to 0.40 ft near Blue and Gray Springs (fig. 16B) is predicted during a simulated drought with a corresponding reduction in streamflow 0.72 ft^3/s or 21.4 percent (compared to non-pumping conditions).

Similarly, simulation of a drought indicates drawdown of 1.10 ft near Balch Spring and 0.40 to 0.50 ft near Blue and Gray Springs resulting from current pumping augmented by new 75 and 100 gal/min production wells (fig 16C), with a corresponding reduction in streamflow 0.77 ft^3/s or 22.9 percent (compared to non- pumping conditions). If existing pumping is augmented by pumping wells 87 and 88 at 100 gal/min each (fig 16D), simulated drawdown during drought is approximately 1.20 ft near Balch Spring, 0.80 ft near Blue Spring, and 0.50 ft near Gray Spring, with a corresponding reduction in streamflow of 0.81 ft^3/s or 24.1 percent (compared to non-pumping conditions). Thus, drawdown in the vicinity of the Center's springs is significantly greater during drought than during normal to above normal hydrologic conditions.

In addition, continual pumping of water from wells 87 and 88 at high rates may cause mining of ground water in the Leetown area and potentially affect the long-term sustainable flow of Balch, Blue, and Gray Springs. Relying on spring flow as much as possible to meet existing and future demands and using production wells used only to augment demands when necessary would minimize this effect. Pumping the new production wells only when necessary would provide time for the water levels to recover and therefore would reduce the potential for ground-water mining. Pumping production wells as little as possible because of their proximity to Center's springs would minimize potential adverse effects on the flow of the springs,

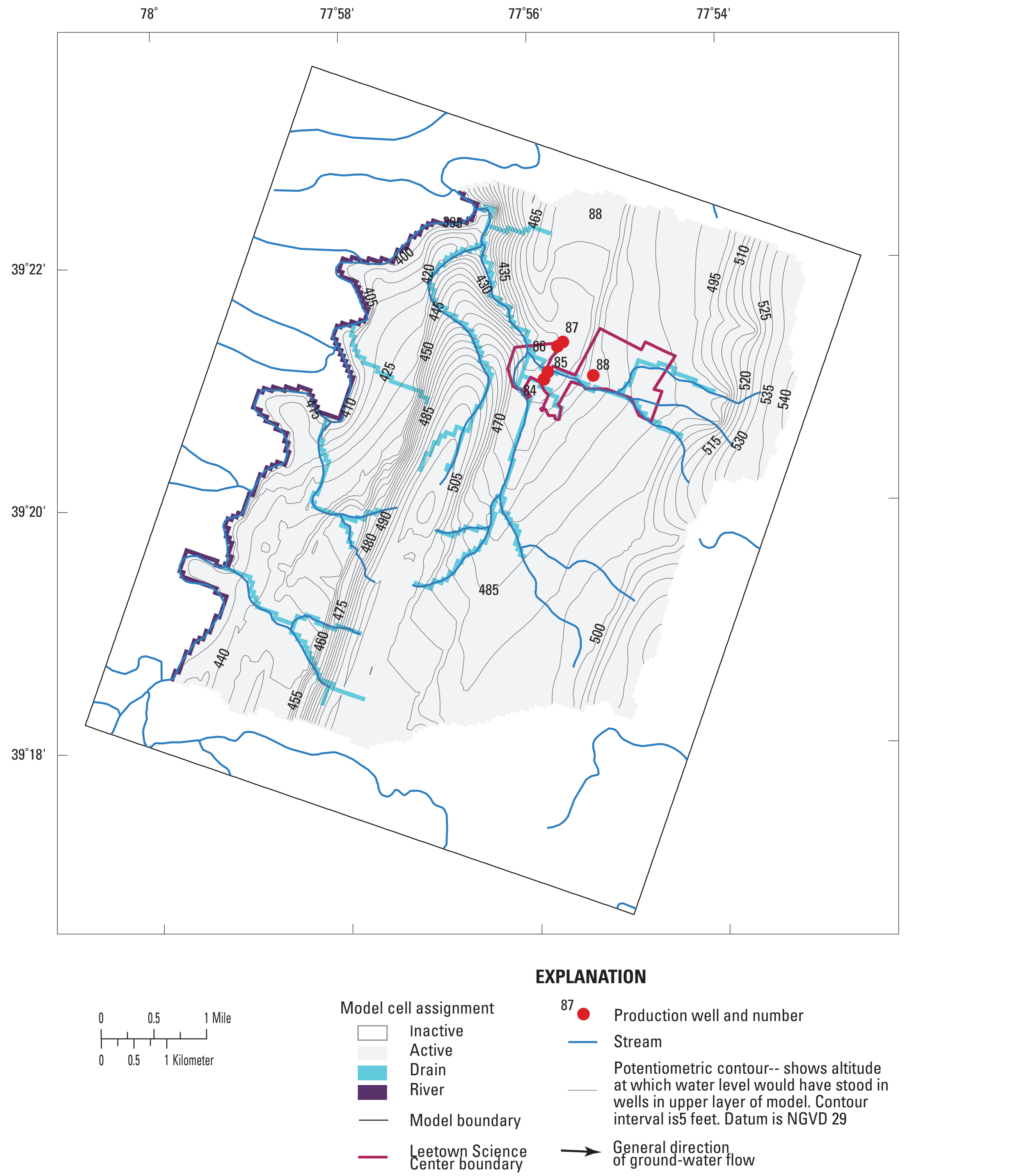


Figure 15. Simulated potentiometric-surface contours in the upper layer of the ground-water flow model of the Leetown area, West Virginia, during a drought.

especially Balch Spring. Because well 88 is isolated from the existing production wells and springs at the Center by the barrier created by the lower conductivity outcrop of Conococheague Limestone (figs. 2 and 8), the effects on water levels and spring flow of pumping well 88 likely would be much less than the effects of pumping well 87. The barrier effect of the Conococheague Limestone is less effective during drought conditions (fig. 16D) than during normal hydrologic conditions (fig. 14D).

Streamflow at the Hopewell Run gaging station also is substantially affected by drought (table 8). Streamflow (based on current withdrawals) is reduced from approximately 10.32

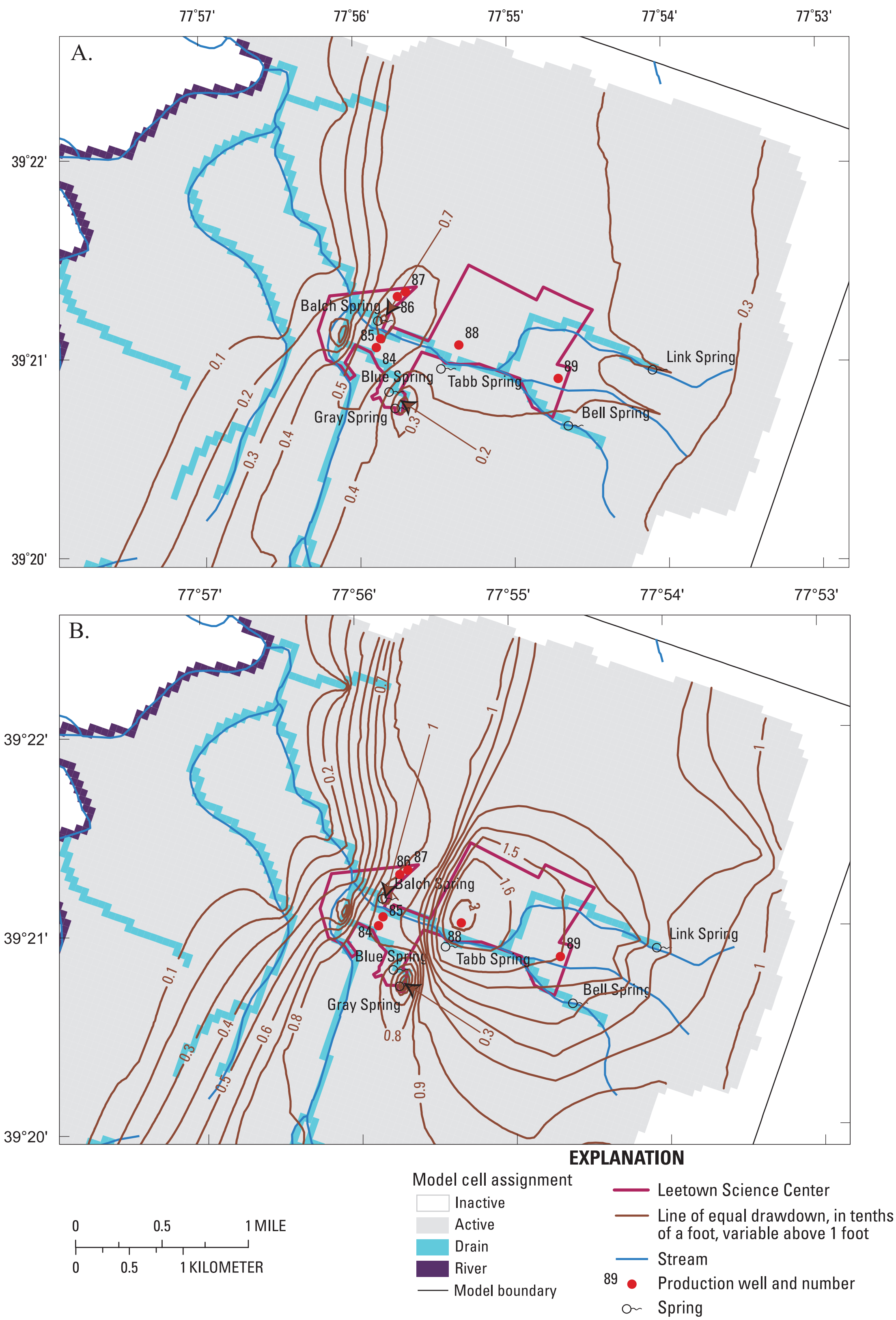


Figure 16. Simulated drawdown in the Leetown area, West Virginia (A) under existing pumping conditions during a drought, and (B) resulting from the addition of production wells 87 and 88 pumping at 50 and 100 gallons per minute during a drought.

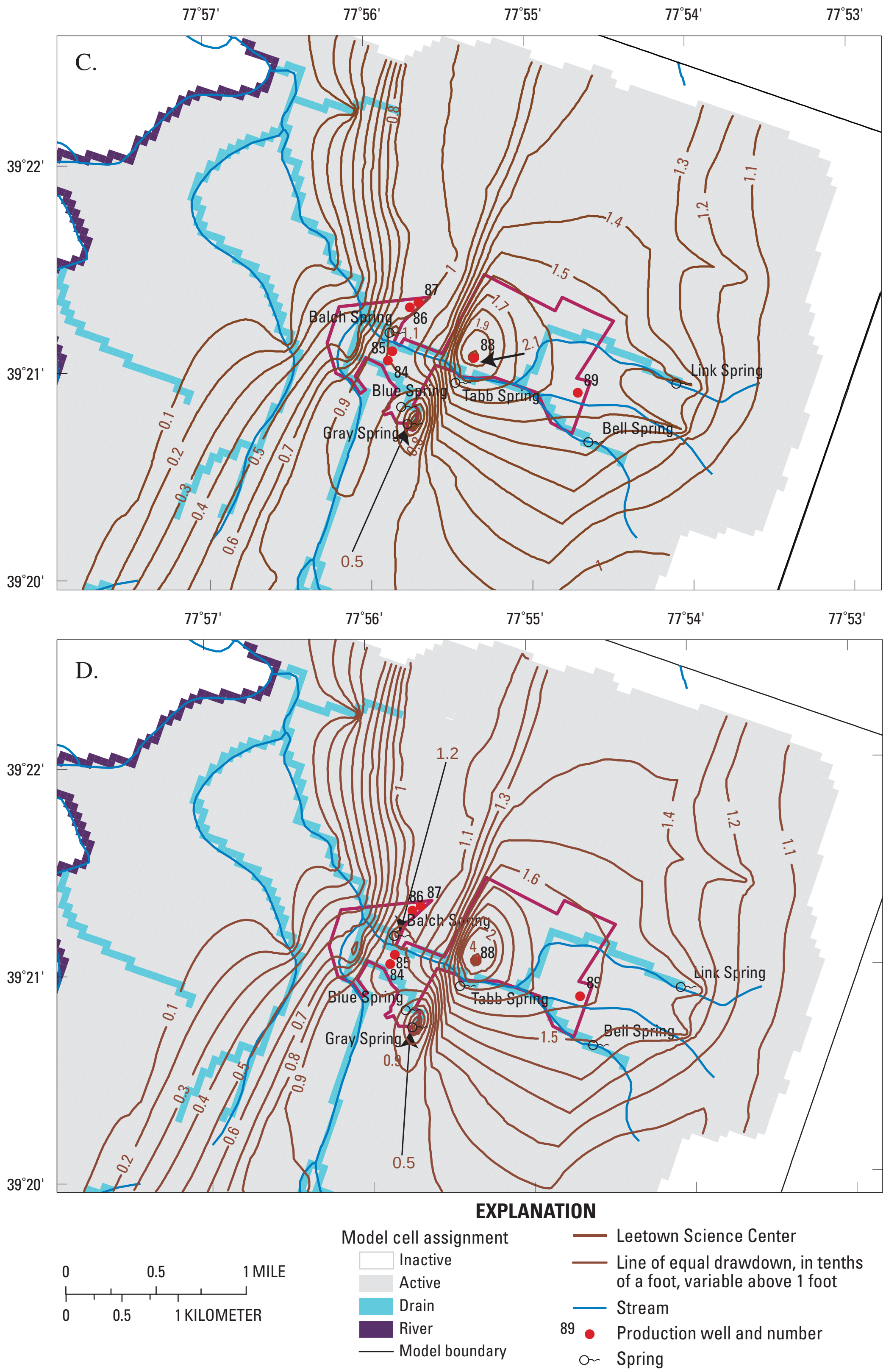


Figure 16. Simulated drawdown in the Leetown area, West Virginia (C) resulting from the addition of production wells 87 and 88 pumping at 75 and 100 gallons per minute during a drought, and (D) resulting from the addition of production wells 87 and 88 pumping at 100 gallons per minute each during a drought.

ft^3/s under normal climatic conditions to 2.90 ft^3/s for a drought (table 8) and a larger percentage of streamflow (13.7 percent) is captured by ground-water withdrawals during drought conditions than during normal conditions (4.7 percent). When two new 100 gal/min production wells are added to augment existing supplies to the Center, the simulated discharge of the stream is reduced by 8.6 percent under normal climatic conditions and 24.1 percent during a simulated drought (table 8). Withdrawals from the new production wells at rates of 150 gal/min, let alone 200 gal/min, are not sustainable during periods of prolonged drought.

Simulated Effects of Suburban Growth

A simulation also was made to evaluate the effect of withdrawals for two hypothetical subdivisions on the hydrology of the Leetown area in areas with development potential. The first subdivision was simulated as a 300-home complex in the northeastern portion of the Hopewell Run watershed and the second was a larger, 500-home complex in the southern portion of the watershed. The subdivisions were assumed to provide water to the three-person homes from single large production wells pumping at rates of 63,000 and 105,000 gal/d (117 gal/min combined pumpage), respectively. It was also assumed that the water would be removed from the basin as interbasin transfer by means of a sewage collection system. These conditions were chosen to simulate a worst-case scenario. The net effect on the hydrology of the watershed of individual homes, each with its own well and septic system, would be less pronounced than the effect of a single large production well with interbasin transfer of waste water. Much of the water withdrawn from individual wells would be returned to the aquifer via septic return flows rather than removed from the watershed. The simulation was based on current withdrawals at the Center, the addition of two new production wells pumping at a combined rate of 200 gal/min, and two subdivision wells pumping at a combined rate of 117 gal/min during normal climatic conditions (table 8). Simulated drawdown resulting from pumping of the two hypothetical subdivision wells is 0.50 ft of drawdown in the vicinity of Balch Spring and 0.10 to 0.20 ft in the vicinity Gray and Blue Springs (fig. 17) with a decrease in streamflow (compared to non-pumping conditions) of 1.18 ft^3/s (10.9 percent) predicted for the watershed during normal conditions. This represents an additional increase in drawdown of approximately 0.20 to 0.30 ft in the vicinity of the Center's springs resulting from the simulated subdivision wells.

During drought conditions, simulated drawdown created by the two hypothetical subdivision and current withdrawals augmented by two new 200 gpm production wells produces 1.5 ft of drawdown in the aquifer in the vicinity of Balch Spring and 1.3 ft near Blue and Gray Springs (fig. 18), and an overall decrease in streamflow (compared to non-pumping conditions) of 1.01 ft^3/s (30.0 percent) predicted for the watershed during drought conditions. This represents an increase of approximately 0.30 ft of drawdown in the vicinity of Balch Spring and 0.50 to 0.80 ft of additional drawdown near Blue and Gray Springs during drought as a result of the simulated subdivision wells. Close monitoring of streamflow and ground- water levels would help to assess potential over-development of the resource.

Limitations of the Simulations

The simulations presented here are based on the best available data but actual drawdown and stream discharge may be greater or lesser than that simulated. In addition, the ground-water flow model was developed as a steady-state simulation, and thus represents long-term conditions. Additional data, especially water-level and streamflow data, not available during the course of this investigation, could be collected during droughts to improve the accuracy of the models. This data could also be used to prepare a transient simulation of ground-water flow. Such a transient simulation may help to determine short-term (monthly or seasonal) effects of ground-water withdrawals.

A major limitation of ground-water modeling in complicated karst terranes is accurate simulation of spring discharge. Springs can either be simulated as withdrawal points (pumping wells) or as drains, but either approach has limitations. For this simulation, Balch Spring was simulated as a withdrawal point and Blue and Gray Springs were simulated as drains. If springs are simulated as withdrawals (pumping wells), a precise discharge from the springs can be specified but cones of depression are commonly observed in such an approach (Early, 2005), which is not realistic. If the springs are simulated as drain nodes, then spring discharge is susceptible to small changes in ground-water levels near the springs. Drains also constrain loss of water back to the aquifer.

A second major limitation of ground-water modeling in complicated karst terranes is related to simulated head (water levels) within the aquifer. A two- or three-foot variation in simulated water levels for this scale of model is considered a very good calibration. However, such a variation in water levels in the vicinity of springs is problematic. Thus, it is extremely difficult to simulate spring flow accurately in a complicated karst aquifer such as that typified by the study area. However, water budgets resulting from a numerical simulation of ground-water flow are not affected as much by these limitations and provide estimates that accurately simulate the streamflow measured for the watershed at the Hopewell Run streamflow-gaging station.

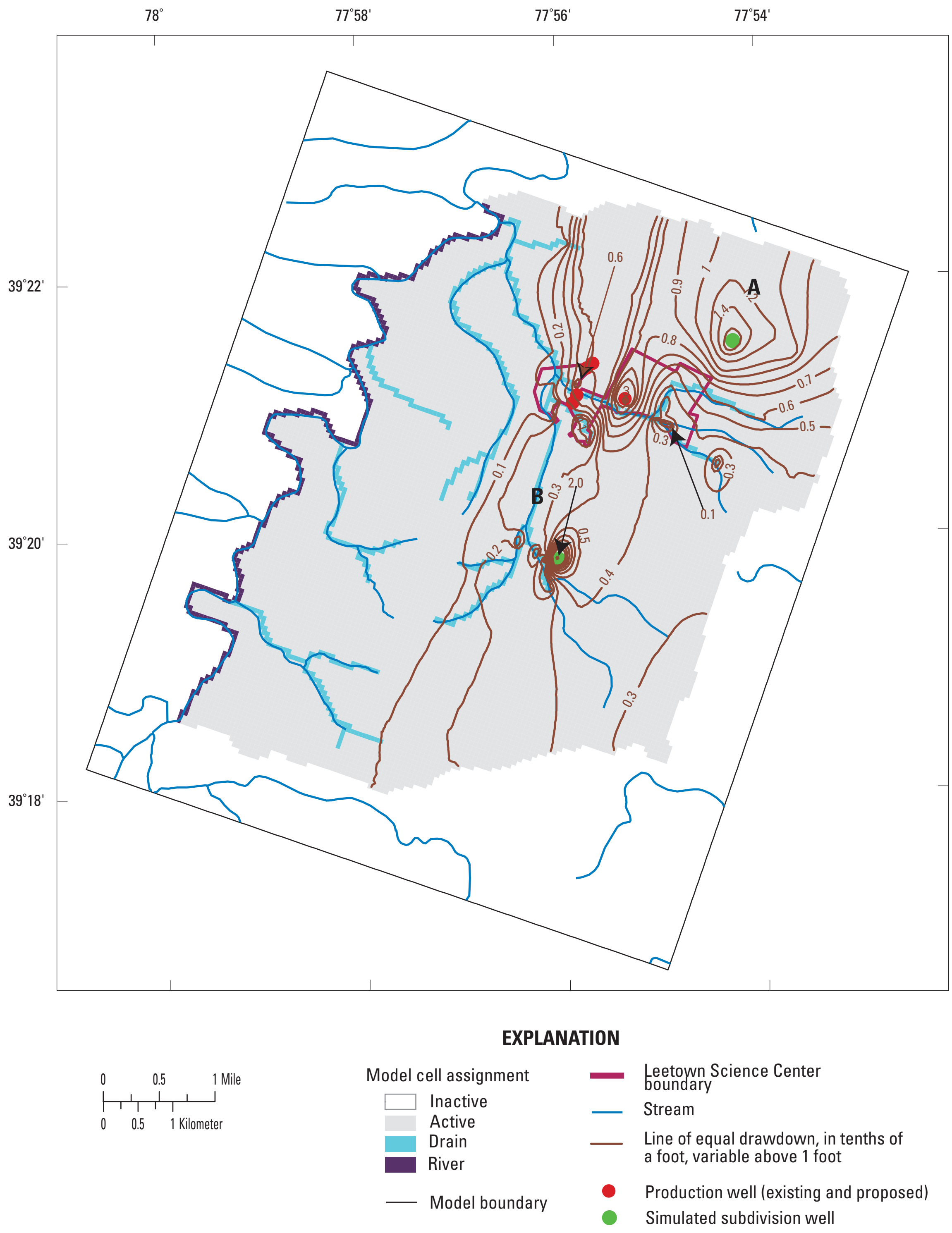


Figure 17. Simulated drawdown in the upper layer of the ground-water flow model of the Leetown area, West Virginia, resulting from the addition of two new production wells at the Leetown Science Center pumping at 100 gallons per minute each, and two hypothetical housing subdivision wells in the Hopewell Run watershed, during normal climatic conditions.

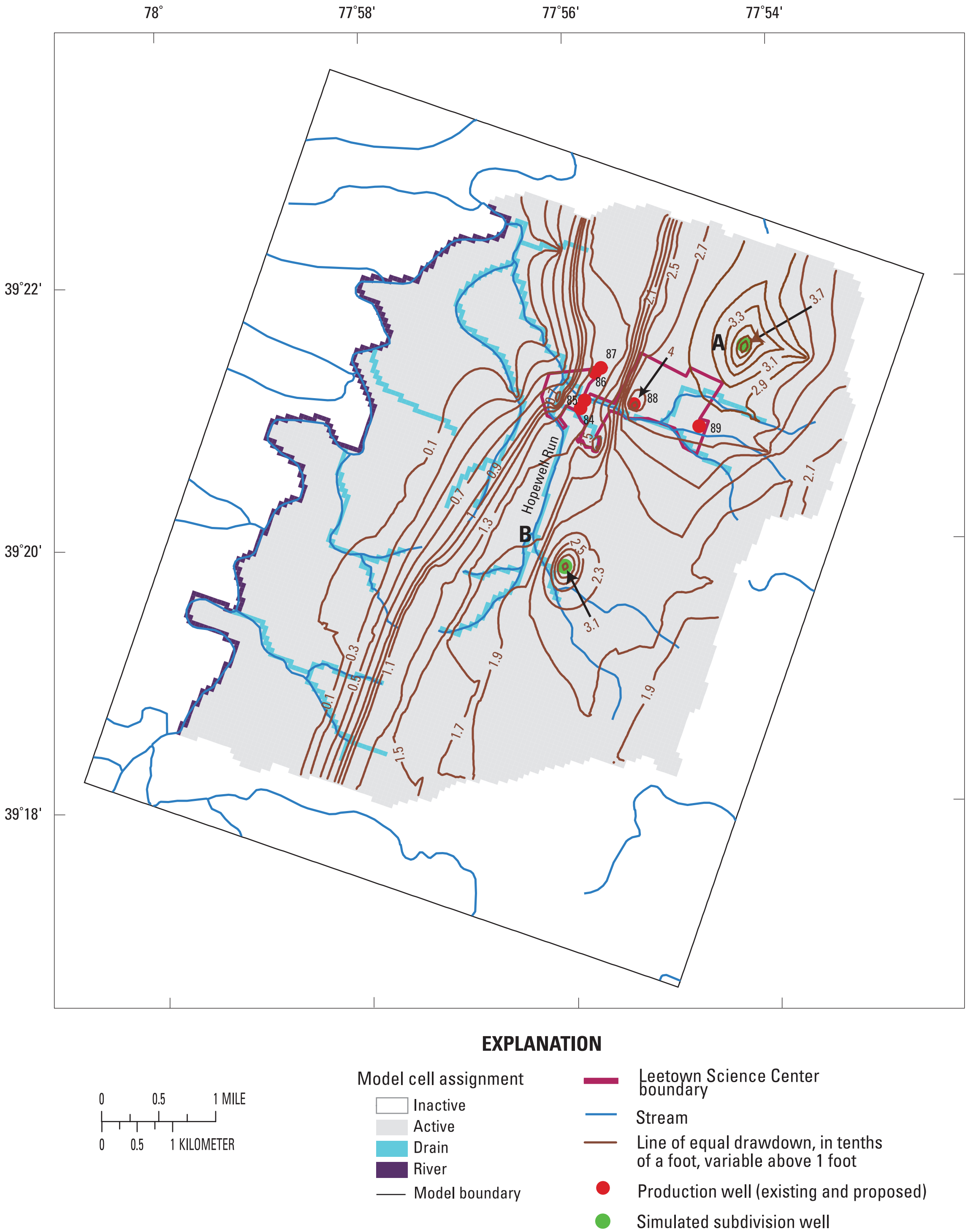


Figure 18. Simulated drawdown in the upper layer of the ground-water flow model of the Leetown area, West Virginia, resulting from the addition of two new production wells at the Leetown Science Center pumping at 100 gallons per minute each, and two hypothetical housing subdivision wells in the Hopewell Run watershed, during a drought.

Summary and Conclusions

Ground-water flow at the USGS Leetown Science Center, West Virginia, and the surrounding area was simulated using a three-dimensional finite-difference model. The ground-water flow model was developed to: (1) test a conceptual model of ground-water flow, (2) develop a budget of available ground-water resources for the Center, (3) define the potential area of recharge for the springs at the Center, (4) simulate pumping scenarios to estimate effects to the springs if additional wells were tapped to augment water supplies, and (5) assess potential effects of drought and suburban development on water availability. The model was a small component of a larger, more comprehensive, multi-disciplinary hydrogeologic assessment of the Leetown area. Development of a numerical model of ground-water flow in the Leetown area would not have been possible without the intensive data-collection and methods development components of the larger, more comprehensive hydrogeologic investigation.

The study area is dominated by karstic carbonate rocks of Cambrian and Ordovician age. Ground water flows through diffuse fractures and small, solutionally enlarged conduits, which serve as drains for the dominant diffuse system of interconnected fractures. Shallow ground-water flow occurs in an epikarstic zone that extends from land surface to a depth of 30 to 60 ft. Most of the residential, production, and commercial wells in the study area are completed in the interval from about 80 to 300 ft below land surface. Hydraulic conductivity decreases with depth in the bedrock aquifer, and ground-water flow occurs primarily in the upper 300 ft of the bedrock. Solutionally enlarged conduits are less pervasive at depths below about 150 ft. Recharge is areally diffuse, occurring over a broad area with minimal focused recharge to sinkholes.

Geologic structure is a major control on ground-water flow. A series of strike-parallel thrust faults and two dominant cross-strike faults act as drains that funnel large quantities of water through the Leetown area. Lithology, especially that of the poorly permeable Conococheague Limestone and Martinsburg Formation, act as a barrier to ground-water flow and retards its downgradient movement. This barrier effect causes ground water to flow laterally along bedding planes and thrust faults. Cross-strike faults and fracture zones allow ground water to flow through the less permeable units. Faults and complex geologic structures (overturned anticlines and synclines) correlate well with the presence of high-yielding wells.

A three-layer numerical ground-water flow model was developed to represent the aquifer based on this conceptual understanding of ground-water flow. The epikarstic upper portion of the aquifer was represented by the upper layer of the model, which extends from land surface to a depth of about 100 ft. The intermediate zone, in which most wells are completed, was represented by the middle layer of the model, and extends from 100 to 300 ft below land surface. The less-fractured, deepest portion of the bedrock aquifer was represented by the lower layer of the model from 300 ft to 450 ft below land surface or approximately sea level(0 ft NAVD88). Areally diffuse recharge was applied to the entire model at a rate of 16.5 in/yr based on estimates of ground-water recharge provided by analyses of streamflow at a station on Hopewell Run in Leetown. Estimates of hydraulic conductivity were made based on results of aquifer tests conducted as part of recent fracture-trace and lineament analysis investigations in Jefferson and Berkeley Counties, West Virginia, and on results of single- and multi-well aquifer tests conducted as part of this investigation. Geologic mapping, conducted as part of this and past investigations, provided the locations of faults and structurally complex folds in the bedrock, and identified the geologic formations that crop out in the area. A fracture-trace and lineament analysis was also conducted for the Leetown area to identify additional possible fracture zones. Surface-geophysical surveys were conducted and LiDAR elevation data were used to verify and identify faults and fracture zones.

Boundary conditions for the model included river nodes along Opequon Creek at the western boundary of the model, drain nodes for Hopewell Run and other minor tributary streams, and no-flow cells for the bedrock ridges separating drainage basins along the northern, eastern, and southern boundaries of the model. Hydraulic conductivities were assigned to the model based on the geologic formations mapped in the area and on the results of aquifer tests. Faults were represented by zones of higher hydraulic conductivity simulating conduit drains.

Various scenarios were simulated to estimate the potential effects on future water-supply alternatives. The model was initially developed and calibrated based on recharge estimated from streamflow data collected at the Hopewell Run streamflow-gaging station from October 2003 through September 2006, results of aquifer tests conducted in Jefferson and Berkeley Counties over the same period, and water-level data collected in the summers of 2004 and 2005. The model was developed as a steady-state simulation. Analysis of head equipotential lines and flow paths from particle-tracking analysis clearly illustrates that surface and ground water over a very broad area are funneled through the Leetown area, including the area occupied by the Center, and are responsible for the large springs at the Center.

The model was then adjusted to simulate current conditions with production wells withdrawing water at average annual rates based on records of pumping maintained by the Center staff. The purpose of the simulation was to assess the effects of current ground-water withdrawals on streamflow and drawdown in the vicinity of existing wells and springs. Analysis of drawdown caused by the current production wells and pumping from Balch Spring indicates that current operations (in 2006) have a minimal effect on ground-water and surface-water resources in the area under normal conditions. Current pumping of ground water diverts 0.51 ft^3/s or 4.7 percent of available streamflow under normal climatic conditions, produces less than 0.10 to 0.20 ft of drawdown around Balch Spring, and approximately 0.10 ft of drawdown in the vicinity of Blue and

Gray Springs.

The model was then used to assess the potential effects of the addition of two new production wells at the Center with average withdrawal rates of 50 and 100 gal/min, respectively. With an additional 150 gal/min augmenting existing supplies, drawdown of approximately 0.30 to 0.40 ft was simulated near Balch Spring and 0.10 ft near Blue and Gray Springs. This represents an additional 0.10 ft of drawdown near Balch Spring. The simulated net effect on streamflow is approximately 0.83 ft^3/s (compared to non pumping conditions), or 7.7 percent (an additional 3 percent compared to current withdrawals) capture of ground water that would have discharged to the stream as base flow. Most of the streamflow captured is ground-water that would have discharged to Hopewell Run or its tributaries. Also, the captured ground-water is only temporarily diverted, because most of the ground-water withdrawn (minus negligible evaporative losses) is returned to the stream by the wastewater-treatment plant at the Center.

Similarly, with an additional 200 gal/min of withdrawals (100 gal/min each) simulated from the two new production wells to augment existing supplies, 0.50 ft of drawdown was simulated near Balch Spring and 0.10 ft of drawdown near Blue and Gray Springs. This represents an additional 0.40 ft of drawdown near Balch Spring and 0.10 to 0.20 ft of drawdown (compared to non pumping conditions) near Blue and Gray Springs. The net effect on streamflow (compared to non pumping conditions) is 0.93 ft^3/s or 8.6-percent (an additional 3.9-percent compared to current withdrawals) capture of ground water that would have discharged to the stream as base flow.

The potential effects of two large subdivisions were assessed by simulating a production well in the northern portion of the study area withdrawing water to supply 300 homes and a production well in the southern portion of the area withdrawing water to supply 500 homes, for a combined additional withdrawal of 117 gal/min. Simulation results indicated an additional drawdown of 0.10 ft near the springs and wells at the Center under normal climatic conditions and current demands increased by an additional 200 gal/min in withdrawals from two new production wells on the Center and 117 gal/min withdrawals from the simulated subdivision wells. Simulated streamflow in Hopewell Run was lowered to 9.65 ft^3/s or 10.9-percent compared to non pumping conditions (an additional 2.3 percent resulting from the subdivision wells). The simulation was conducted assuming interbasin transfer of water by means of a sewage collection system. The effect on water availability would be reduced if the water is returned either to Hopewell Run or by septic-return flows.

Finally, a drought was simulated by reducing recharge within the model to 8.3 in/yr, a rate that approximates the recharge during the prolonged 16-month drought that affected the region from late 1998 to early 2000. In these simulations, existing wells were pumped at current rates but two new production wells were pumped at rates of either 50 and 100 gal/min, 75 and 100 gal/min, or 100 gal/min each. Regardless of the specific scenario simulated, drawdown produced by the augmented withdrawals during a drought is substantial in the vicinity of the Center's springs. Simulated drawdown in the vicinity of Blue and Gray Springs ranges from 0.3 to 0.5 ft and drawdown in the vicinity of Balch Spring ranges from 0.6 to 1.0 ft for the withdrawal scenarios. This amount of drawdown would substantially decrease the flow of Balch, Blue, and Gray Springs and the streamflow in Hopewell Run. Therefore, on the basis of the simulations, withdrawal of water at current rates combined with the additional 150 to 200 gal/min withdrawal from the new production wells likely is not sustainable for long periods during droughts. Close monitoring of water levels and streamflow during critical low-flow periods would help avoid adverse impacts of ground-water withdrawals.

Future water-use planning by water-resource managers could take into consideration the fact that streamflow in the region has been anomalously high since 1970. Availability of ground and surface water in the future, especially during low-flow periods, is likely to be less than in recent years. The drought was simulated at steady-state conditions by assuming a drought for a period similar to that of 1999. Drawdown in the production wells at the Center would be less severe during a drought of shorter duration, because stream or spring flow could likely be sustained by storage of water within the aquifer.

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Appendices

Appendix 1: Monthly water-level data for 17 wells in the Leetown area, West Virginia, July 2003 - September 2005.

Appendix 2: Daily mean streamflow at the Hopewell Run at Leetown, West Virginia, gaging station, April 2002 - March 2006.

Appendix 3: Water-levels in observation wells used in calibration of the ground-water flow model of the Leetown area, West Virginia.

Appendix 4: Precipitation at Gray Spring at Leetown, West Virginia, November 2002 -September 2005.

Appendix 1. -- Monthly water-level data for 17 wells in the Leetown area, West Virginia, July 2003 - September 2005.

[NAVD 88, North American Vertical Datum of 1988]

Local well number	Local well name	Date measured	Water level (feet below land surface)	Water-level altitude (feet above NAVD88)	Local well number	Local well name	Date measured	Water level (feet below land surface)	Water-level altitude (feet above NAVD88)
Jef-0593	Tabb upper piezometer	07/21/03	15.26	491.66	Jef-0594	Tabb lower piezometer	07/21/03	3.34	488.33
Jef-0593		08/19/03	17.23	489.69	Jef-0594		08/19/03	4.91	486.76
Jef-0593		09/23/03	14.84	492.08	Jef-0594		09/24/03	3.77	487.90
Jef-0593		10/28/03	16.92	490.00	Jef-0594		10/28/03	4.64	487.03
Jef-0593		11/18/03	16.90	490.02	Jef-0594		11/18/03	4.52	487.15
Jef-0593		12/30/03	13.02	493.90	Jef-0594		12/30/03	1.23	490.44
Jef-0593		01/16/04	14.63	492.29	Jef-0594		01/16/04	2.84	488.83
Jef-0593		02/23/04	12.29	494.63	Jef-0594		02/23/04	1.03	490.64
Jef-0593		03/24/04	14.81	492.11	Jef-0594		03/24/04	2.91	488.76
Jef-0593		04/21/04	13.21	493.71	Jef-0594		04/21/04	1.33	490.34
Jef-0593		05/25/04	14.74	492.18	Jef-0594		05/25/04	2.60	489.07
Jef-0593		06/22/04	14.38	492.54	Jef-0594		06/22/04	2.37	489.30
Jef-0593		07/20/04	17.33	489.59	Jef-0594		07/20/04	4.84	486.83
Jef-0593		08/23/04	18.66	488.26	Jef-0594		08/23/04	5.80	485.87
Jef-0593		09/20/04	19.15	487.77	Jef-0594		09/20/04	6.20	485.47
Jef-0593		10/21/04	18.44	488.48	Jef-0594		10/21/04	5.69	485.98
Jef-0593		11/16/04	18.47	488.45	Jef-0594		11/16/04	5.62	486.05
Jef-0593		01/04/05	17.27	489.65	Jef-0594		01/04/05	4.83	486.84
Jef-0593		01/26/05	16.79	490.13	Jef-0594		01/26/05	4.44	487.23
Jef-0593		02/17/05	17.81	489.11	Jef-0594		02/17/05	5.22	486.45
Jef-0593		03/17/05	18.02	488.90	Jef-0594		03/17/05	5.36	486.31
Jef-0593		04/18/05	13.77	493.15	Jef-0594		04/18/05	2.11	489.56
Jef-0593		06/02/05	17.46	489.46	Jef-0594		06/02/05	4.95	486.72
Jef-0593		06/20/05	18.45	488.47	Jef-0594		06/20/05	4.61	487.06
Jef-0593		07/12/05	19.08	487.84	Jef-0594		07/12/05	6.14	485.53
Jef-0593		08/03/05	19.69	487.23	Jef-0594		08/03/05	6.60	485.07
Jef-0593		08/22/05	20.18	486.74	Jef-0594		08/22/05	7.00	484.67
Jef-0593		09/15/05	20.83	486.09	Jef-0594		09/15/05	7.44	484.23
Jef-0584	Bone yard upper well	09/26/03	19.09	460.07	Jef-0591	Bone yard lower well	09/26/03	16.24	459.80
Jef-0584		10/28/03	20.43	458.73	Jef-0591		10/28/03	17.80	458.24
Jef-0584		12/30/03	19.37	459.79	Jef-0591		12/30/03	16.69	459.35
Jef-0584		01/16/04	20.84	458.32	Jef-0591		01/16/04	18.19	457.85
Jef-0584		02/23/04	19.17	459.99	Jef-0591		02/23/04	16.86	459.18
Jef-0584		03/24/04	20.84	458.32	Jef-0591		03/24/04	18.26	457.78

Appendix 1. -- Monthly water-level data for 17 wells in the Leetown area, West Virginia, July 2003 - September 2005.—Continued

[NAVD 88, North American Vertical Datum of 1988]

Local well number	Local well name	Date measured	Water level (feet below land surface)	Water-level altitude (feet above NAVD88)	Local well number	Local well name	Date measured	Water level (feet below land surface)	Water-level altitude (feet above NAVD88)
Jef-0584		04/21/04	20.18	458.98	Jef-0591		04/21/04	17.73	458.31
Jef-0584		05/25/04	20.93	458.23	Jef-0591		05/25/04	18.33	457.71
Jef-0584		06/22/04	20.51	458.65	Jef-0591		06/22/04	18.01	458.03
Jef-0584		07/20/04	21.88	457.28	Jef-0591		07/20/04	19.43	456.61
Jef-0584		08/23/04	23.41	455.75	Jef-0591		08/23/04	21.47	454.57
Jef-0584		09/20/04	22.23	456.93	Jef-0591		09/20/04	19.72	456.32
Jef-0584		10/21/04	20.82	458.34	Jef-0591		10/21/04	18.05	457.99
Jef-0584		11/16/04	20.49	458.67	Jef-0591		11/16/04	17.72	458.32
Jef-0584		01/04/05	20.27	458.89	Jef-0591		01/04/05	17.44	458.60
Jef-0584		01/26/05	20.49	458.67	Jef-0591		01/26/05	17.73	458.31
Jef-0584		02/17/05	21.93	457.23	Jef-0591		02/17/05	18.26	457.78
Jef-0584		03/17/05	20.93	458.23	Jef-0591		03/17/05	18.25	457.79
Jef-0584		04/18/05	17.94	461.22	Jef-0591		04/18/05	15.13	460.91
Jef-0584		06/02/05	19.18	459.98	Jef-0591		06/02/05	16.42	459.62
Jef-0584		06/20/05	19.75	459.41	Jef-0591		06/20/05	17.03	459.01
Jef-0584		07/12/05	20.69	458.47	Jef-0591		07/12/05	18.46	457.58
Jef-0584		08/03/05	20.70	458.46	Jef-0591		08/03/05	18.47	457.57
Jef-0584		08/22/05	22.00	457.16	Jef-0591		08/22/05	19.96	456.08
Jef-0584		09/15/05	22.31	456.85	Jef-0591		09/15/05	20.10	455.94
Jef-0588	Syncline well	07/21/03	--	--	Jef-0600	Syncline piezometer	07/21/03	8.50	500.80
Jef-0588		08/19/03	--	--	Jef-0600		08/19/03	11.59	497.71
Jef-0588		09/23/03	13.24	499.34	Jef-0600		09/23/03	9.98	499.32
Jef-0588		10/28/03	14.75	497.83	Jef-0600		10/28/03	11.49	497.81
Jef-0588		11/18/03	14.24	498.34	Jef-0600		11/18/03	10.97	498.33
Jef-0588		12/30/03	8.01	504.57	Jef-0600		12/30/03	4.77	504.53
Jef-0588		01/16/04	11.35	501.23	Jef-0600		01/16/04	8.12	501.18
Jef-0588		02/23/04	8.15	504.43	Jef-0600		02/23/04	4.51	504.79
Jef-0588		03/24/04	11.24	501.34	Jef-0600		03/24/04	8.01	501.29
Jef-0588		04/21/04	8.09	504.49	Jef-0600		04/21/04	4.82	504.48
Jef-0588		05/25/04	11.33	501.25	Jef-0600		05/25/04	8.08	501.22
Jef-0588		06/22/04	11.69	500.89	Jef-0600		06/22/04	8.44	500.86
Jef-0588		07/20/04	15.13	497.45	Jef-0600		07/20/04	11.87	497.43
Jef-0588		08/23/04	16.66	495.92	Jef-0600		08/23/04	13.40	495.90
Jef-0588		09/20/04	17.40	495.18	Jef-0600		09/20/04	14.15	495.15

Appendix 1. -- Monthly water-level data for 17 wells in the Leetown area, West Virginia, July 2003 - September 2005.—Continued

[NAVD 88, North American Vertical Datum of 1988]

Local well number	Local well name	Date measured	Water level (feet below land surface)	Water-level altitude (feet above NAVD88)	Local well number	Local well name	Date measured	Water level (feet below land surface)	Water-level altitude (feet above NAVD88)
Jef-0588		10/21/04	16.20	496.38	Jef-0600		10/21/04	12.96	496.34
Jef-0588		11/16/04	15.85	496.73	Jef-0600		11/16/04	12.60	496.70
Jef-0588		01/04/05	14.10	498.48	Jef-0600		01/04/05	10.83	498.47
Jef-0588		01/26/05	13.72	498.86	Jef-0600		01/26/05	10.43	498.87
Jef-0588		02/17/05	15.31	497.27	Jef-0600		02/17/05	12.04	497.26
Jef-0588		03/17/05	15.35	497.23	Jef-0600		03/17/05	12.08	497.22
Jef-0588		04/18/05	9.26	503.32	Jef-0600		04/18/05	6.05	503.25
Jef-0588		06/02/05	15.11	497.47	Jef-0600		06/02/05	11.86	497.44
Jef-0588		06/20/05	16.24	496.34	Jef-0600		06/20/05	13.01	496.29
Jef-0588		07/12/05	17.21	495.37	Jef-0600		07/12/05	13.96	495.34
Jef-0588		08/03/05	18.10	494.48	Jef-0600		08/03/05	14.81	494.49
Jef-0588		08/22/05	19.03	493.55	Jef-0600		08/22/05	15.99	493.31
Jef-0588		09/15/05	19.93	492.65	Jef-0600		09/15/05	16.70	492.60
Jef-0590	Ball field well	07/21/03	--	--	Jef-0595	Ball field piezometer	07/21/03	17.87	459.52
Jef-0590		08/19/03	--	--	Jef-0595		08/19/03	18.70	458.69
Jef-0590		09/26/03	17.07	460.99	Jef-0595		09/23/03	16.24	461.15
Jef-0590		10/28/03	19.33	458.73	Jef-0595		10/28/03	18.64	458.75
Jef-0590		11/18/03	19.06	459.00	Jef-0595		11/18/03	18.38	459.01
Jef-0590		12/30/03	18.13	459.93	Jef-0595		12/30/03	17.41	459.98
Jef-0590		01/16/04	19.79	458.27	Jef-0595		01/16/04	19.09	458.30
Jef-0590		02/23/04	18.61	459.45	Jef-0595		02/23/04	17.50	459.89
Jef-0590		03/24/04	20.00	458.06	Jef-0595		03/24/04	19.31	458.08
Jef-0590		04/21/04	19.37	458.69	Jef-0595		04/21/04	18.68	458.71
Jef-0590		05/25/04	20.02	458.04	Jef-0595		05/25/04	19.33	458.06
Jef-0590		06/22/04	19.77	458.29	Jef-0595		06/22/04	19.09	458.30
Jef-0590		07/20/04	21.33	456.73	Jef-0595		07/20/04	20.65	456.74
Jef-0590		08/23/04	23.67	454.39	Jef-0595		08/23/04	22.99	454.40
Jef-0590		09/20/04	21.63	456.43	Jef-0595		09/20/04	20.97	456.42
Jef-0590		10/21/04	19.61	458.45	Jef-0595		10/21/04	18.90	458.49
Jef-0590		11/16/04	19.19	458.87	Jef-0595		11/16/04	18.48	458.91
Jef-0590		01/04/05	18.84	459.22	Jef-0595		01/04/05	18.11	459.28
Jef-0590		01/26/05	19.11	458.95	Jef-0595		01/26/05	18.37	459.02
Jef-0590		02/17/05	19.66	458.40	Jef-0595		02/17/05	18.92	458.47
Jef-0590		03/17/05	19.16	458.90	Jef-0595		03/17/05	18.36	459.03

Appendix 1. -- Monthly water-level data for 17 wells in the Leetown area, West Virginia, July 2003 - September 2005.—Continued

[NAVD 88, North American Vertical Datum of 1988]

Local well number	Local well name	Date measured	Water level (feet below land surface)	Water-level altitude (feet above NAVD88)	Local well number	Local well name	Date measured	Water level (feet below land surface)	Water-level altitude (feet above NAVD88)
Jef-0590		04/18/05	15.40	462.66	Jef-0595		04/18/05	14.54	462.85
Jef-0590		06/02/05	16.89	461.17	Jef-0595		06/02/05	16.04	461.35
Jef-0590		06/20/05	18.03	460.03	Jef-0595		06/20/05	17.24	460.15
Jef-0590		07/12/05	20.03	458.03	Jef-0595		07/12/05	19.31	458.08
Jef-0590		08/03/05	20.08	457.98	Jef-0595		08/03/05	19.38	458.01
Jef-0590		08/22/05	21.95	456.11	Jef-0595		08/22/05	21.30	456.09
Jef-0590		09/15/05	22.13	455.93	Jef-0595		09/15/05	21.46	455.93
Jef-0589	Anticline well	07/21/03	--	--	Jef-0598	Anticline piezometer	07/21/03	15.75	499.68
Jef-0589		08/19/03	--	--	Jef-0598		08/19/03	18.86	496.57
Jef-0589		09/23/03	18.33	498.43	Jef-0598		09/23/03	17.01	498.42
Jef-0589		10/28/03	19.01	497.75	Jef-0598		10/28/03	18.69	496.74
Jef-0589		11/18/03	19.59	497.17	Jef-0598		11/18/03	18.53	496.90
Jef-0589		12/30/03	13.36	503.40	Jef-0598		12/30/03	12.08	503.35
Jef-0589		01/16/04	16.60	500.16	Jef-0598		01/16/04	15.28	500.15
Jef-0589		02/23/04	13.48	503.28	Jef-0598		02/23/04	11.90	503.53
Jef-0589		03/24/04	16.62	500.14	Jef-0598		03/24/04	15.23	500.20
Jef-0589		04/21/04	13.60	503.16	Jef-0598		04/21/04	12.32	503.11
Jef-0589		05/25/04	16.59	500.17	Jef-0598		05/25/04	15.27	500.16
Jef-0589		06/22/04	16.89	499.87	Jef-0598		06/22/04	15.59	499.84
Jef-0589		07/20/04	20.48	496.28	Jef-0598		07/20/04	19.16	496.27
Jef-0589		08/23/04	21.89	494.87	Jef-0598		08/23/04	20.58	494.85
Jef-0589		09/20/04	22.51	494.25	Jef-0598		09/20/04	21.18	494.25
Jef-0589		10/21/04	21.42	495.34	Jef-0598		10/21/04	20.11	495.32
Jef-0589		11/16/04	21.19	495.57	Jef-0598		11/16/04	19.86	495.57
Jef-0589		01/04/05	19.43	497.33	Jef-0598		01/04/05	18.10	497.33
Jef-0589		01/26/05	19.06	497.70	Jef-0598		01/26/05	17.73	497.70
Jef-0589		02/17/05	20.63	496.13	Jef-0598		02/17/05	19.29	496.14
Jef-0589		03/17/05	20.70	496.06	Jef-0598		03/17/05	19.37	496.06
Jef-0589		04/18/05	14.51	502.25	Jef-0598		04/18/05	13.19	502.24
Jef-0589		06/02/05	20.49	496.27	Jef-0598		06/02/05	19.17	496.26
Jef-0589		06/20/05	21.55	495.21	Jef-0598		06/20/05	20.25	495.18
Jef-0589		07/12/05	22.39	494.37	Jef-0598		07/12/05	21.07	494.36
Jef-0589		08/03/05	23.18	493.58	Jef-0598		08/03/05	21.84	493.59
Jef-0589		08/22/05	23.93	492.83	Jef-0598		08/22/05	22.59	492.84

Appendix 1. -- Monthly water-level data for 17 wells in the Leetown area, West Virginia, July 2003 - September 2005.—Continued

[NAVD 88, North American Vertical Datum of 1988]

Local well number	Local well name	Date measured	Water level (feet below land surface)	Water-level altitude (feet above NAVD88)	Local well number	Local well name	Date measured	Water level (feet below land surface)	Water-level altitude (feet above NAVD88)
Jef-0589		09/15/05	24.79	491.97	Jef-0598		09/15/05	23.45	491.98
Jef-0587	Low road well	07/21/03	--	--	Jef-0596	Low road piezometer	07/21/03	46.89	487.15
Jef-0587		08/19/03	--	--	Jef-0596		08/19/03	47.03	487.01
Jef-0587		09/23/03	45.98	487.95	Jef-0596		09/23/03	46.72	487.32
Jef-0587		10/28/03	46.86	487.07	Jef-0596		10/28/03	46.96	487.08
Jef-0587		11/18/03	46.72	487.21	Jef-0596		11/18/03	46.82	487.22
Jef-0587		12/30/03	43.19	490.74	Jef-0596		12/30/03	43.45	490.59
Jef-0587		01/16/04	45.90	488.03	Jef-0596		01/16/04	46.17	487.87
Jef-0587		02/23/04	42.06	491.87	Jef-0596		02/23/04	41.74	492.30
Jef-0587		03/24/04	45.79	488.14	Jef-0596		03/24/04	45.98	488.06
Jef-0587		04/21/04	42.39	491.54	Jef-0596		04/21/04	42.50	491.54
Jef-0587		06/22/04	46.07	487.86	Jef-0596		06/22/04	46.28	487.76
Jef-0587		07/20/04	47.17	486.76	Jef-0596		07/20/04	47.17	486.87
Jef-0587		08/23/04	47.40	486.53	Jef-0596		08/23/04	47.39	486.65
Jef-0587		09/20/04	47.22	486.71	Jef-0596		09/20/04	47.23	486.81
Jef-0587		10/21/04	47.01	486.92	Jef-0596		10/21/04	47.08	486.96
Jef-0587		11/16/04	46.89	487.04	Jef-0596		11/16/04	46.94	487.10
Jef-0587		01/04/05	46.59	487.34	Jef-0596		01/04/05	46.70	487.34
Jef-0587		01/26/05	46.34	487.59	Jef-0596		01/26/05	46.45	487.59
Jef-0587		02/17/05	46.79	487.14	Jef-0596		02/17/05	46.85	487.19
Jef-0587		03/17/05	46.74	487.19	Jef-0596		03/17/05	46.78	487.26
Jef-0587		04/18/05	44.55	489.38	Jef-0596		04/18/05	44.84	489.20
Jef-0587		06/02/05	46.96	486.97	Jef-0596		06/02/05	46.96	487.08
Jef-0587		06/20/05	47.31	486.62	Jef-0596		06/20/05	47.24	486.80
Jef-0587		07/12/05	47.50	486.43	Jef-0596		07/12/05	47.40	486.64
Jef-0587		08/03/05	47.84	486.09	Jef-0596		08/03/05	47.68	486.36
Jef-0587		08/22/05	48.09	485.84	Jef-0596		08/22/05	47.94	486.10
Jef-0587		09/15/05	48.61	485.32	Jef-0596		09/15/05	48.48	485.56
Jef-0586	USDA fault well	07/21/03	--	--	Jef-0599	USDA piezometer	07/21/03	14.77	456.53
Jef-0586		08/19/03	--	--	Jef-0599		08/19/03	15.38	455.92
Jef-0586		09/23/03	15.57	456.98	Jef-0599		09/23/03	13.62	457.68
Jef-0586		10/28/03	16.42	456.13	Jef-0599		10/28/03	15.13	456.17
Jef-0586		11/18/03	16.49	456.06	Jef-0599		11/18/03	15.23	456.07
Jef-0586		12/30/03	--	--	Jef-0599		12/30/03	13.54	457.76

Appendix 1. -- Monthly water-level data for 17 wells in the Leetown area, West Virginia, July 2003 - September 2005.—Continued

[NAVD 88, North American Vertical Datum of 1988]

Local well number	Local well name	Date measured	Water level (feet below land surface)	Water-level altitude (feet above NAVD88)	Local well number	Local well name	Date measured	Water level (feet below land surface)	Water-level altitude (feet above NAVD88)
Jef-0586		01/16/04	--	--	Jef-0599		01/16/04	15.02	456.28
Jef-0586		02/23/04	--	--	Jef-0599		02/23/04	12.65	458.65
Jef-0586		03/24/04	--	--	Jef-0599		03/24/04	15.17	456.13
Jef-0586		04/21/04	--	--	Jef-0599		04/21/04	14.08	457.22
Jef-0586		05/25/04	16.49	456.06	Jef-0599		05/25/04	15.20	456.10
Jef-0586		06/22/04	16.53	456.02	Jef-0599		06/22/04	15.26	456.04
Jef-0586		07/20/04	18.15	454.40	Jef-0599		07/20/04	16.89	454.41
Jef-0586		08/23/04	19.55	453.00	Jef-0599		08/23/04	18.29	453.01
Jef-0586		09/20/04	17.53	455.02	Jef-0599		09/20/04	16.28	455.02
Jef-0586		10/21/04	16.84	455.71	Jef-0599		10/21/04	15.57	455.73
Jef-0586		11/16/04	16.79	455.76	Jef-0599		11/16/04	15.53	455.77
Jef-0586		01/04/05	16.74	455.81	Jef-0599		01/04/05	15.46	455.84
Jef-0586		01/26/05	17.23	455.32	Jef-0599		01/26/05	16.02	455.28
Jef-0586		02/17/05	17.00	455.55	Jef-0599		02/17/05	15.74	455.56
Jef-0586		03/17/05	17.46	455.09	Jef-0599		03/17/05	16.22	455.08
Jef-0586		04/18/05	15.58	456.97	Jef-0599		04/18/05	14.30	457.00
Jef-0586		06/02/05	17.27	455.28	Jef-0599		06/02/05	15.99	455.31
Jef-0586		06/20/05	17.31	455.24	Jef-0599		06/20/05	16.07	455.23
Jef-0586		07/12/05	18.00	454.55	Jef-0599		07/12/05	16.72	454.58
Jef-0586		08/03/05	17.90	454.65	Jef-0599		08/03/05	16.65	454.65
Jef-0586		08/22/05	17.97	454.58	Jef-0599		08/22/05	16.67	454.63
Jef-0586		09/15/05	18.12	454.43	Jef-0599		09/15/05	16.86	454.44
Jef-0585	Stable B well	09/23/03	34.43	495.46	Jef-0592	Stable C well	09/23/03	33.65	494.90
Jef-0585		10/28/03	35.92	493.97	Jef-0592		10/28/03	34.70	493.85
Jef-0585		11/18/03	35.44	494.45	Jef-0592		11/18/03	34.26	494.29
Jef-0585		12/30/03	29.36	500.53	Jef-0592		12/30/03	28.51	500.04
Jef-0585		01/16/04	32.74	497.15	Jef-0592		01/16/04	31.62	496.93
Jef-0585		02/23/04	29.38	500.51	Jef-0592		02/23/04	28.70	499.85
Jef-0585		03/24/04	32.82	497.07	Jef-0592		03/24/04	31.73	496.82
Jef-0585		04/21/04	29.81	500.08	Jef-0592		04/21/04	28.80	499.75
Jef-0585		05/25/04	33.07	496.82	Jef-0592		05/25/04	31.98	496.57
Jef-0585		06/22/04	33.25	496.64	Jef-0592		06/22/04	32.17	496.38
Jef-0585		07/20/04	36.78	493.11	Jef-0592		07/20/04	35.40	493.15
Jef-0585		08/23/04	38.04	491.85	Jef-0592		08/23/04	36.68	491.87

Appendix 1. -- Monthly water-level data for 17 wells in the Leetown area, West Virginia, July 2003 - September 2005.—Continued

[NAVD 88, North American Vertical Datum of 1988]

Local well number	Local well name	Date measured	Water level (feet below land surface)	Water-level altitude (feet above NAVD88)	Local well number	Local well name	Date measured	Water level (feet below land surface)	Water-level altitude (feet above NAVD88)
Jef-0585		09/20/04	38.45	491.44	Jef-0592		09/20/04	37.08	491.47
Jef-0585		10/21/04	37.22	492.67	Jef-0592		10/21/04	35.87	492.68
Jef-0585		11/16/04	36.98	492.91	Jef-0592		11/16/04	35.71	492.84
Jef-0585		01/04/05	35.06	494.83	Jef-0592		01/04/05	33.80	494.75
Jef-0585		01/26/05	34.66	495.23	Jef-0592		01/26/05	33.42	495.13
Jef-0585		02/17/05	36.39	493.50	Jef-0592		02/17/05	35.06	493.49
Jef-0585		03/17/05	36.37	493.52	Jef-0592		03/17/05	35.04	493.51
Jef-0585		04/18/05	30.80	499.09	Jef-0592		04/18/05	29.76	498.79
Jef-0585		06/02/05	36.49	493.40	Jef-0592		06/02/05	35.17	493.38
Jef-0585		06/20/05	37.68	492.21	Jef-0592		06/20/05	36.35	492.20
Jef-0585		07/12/05	38.55	491.34	Jef-0592		07/12/05	37.15	491.40
Jef-0585		08/03/05	39.42	490.47	Jef-0592		08/03/05	38.00	490.55
Jef-0585		08/22/05	40.08	489.81	Jef-0592		08/22/05	38.66	489.89
Jef-0585		09/15/05	40.81	489.08	Jef-0592		09/15/05	39.37	489.18
Jef-0601	Stable A well	07/21/03	36.45	495.91	Jef-0597	Stable piezometer	07/21/03	32.78	496.21
Jef-0601		08/19/03	39.20	493.16	Jef-0597		08/19/03	35.67	493.32
Jef-0601		09/23/03	37.51	494.85	Jef-0597		09/23/03	34.03	494.96
Jef-0601		10/28/03	38.62	493.74	Jef-0597		10/28/03	35.10	493.89
Jef-0601		11/18/03	38.08	494.28	Jef-0597		11/18/03	34.66	494.33
Jef-0601		12/30/03	32.56	499.80	Jef-0597		12/30/03	28.81	500.18
Jef-0601		01/16/04	35.62	496.74	Jef-0597		01/16/04	31.96	497.03
Jef-0601		02/23/04	32.45	499.91	Jef-0597		02/23/04	28.80	500.19
Jef-0601		03/24/04	35.73	496.63	Jef-0597		03/24/04	35.08	493.91
Jef-0601		04/21/04	32.86	499.50	Jef-0597		04/21/04	29.12	499.87
Jef-0601		05/25/04	36.01	496.35	Jef-0597		05/25/04	32.35	496.64
Jef-0601		06/22/04	36.22	496.14	Jef-0597		06/22/04	32.53	496.46
Jef-0601		07/20/04	39.31	493.05	Jef-0597		07/20/04	35.80	493.19

Appendix 2. Daily mean streamflow in ft3/s measured at the Hopewell Run streamflow-gaging station, Leetown, West Virginia, April 2002 - March 2006.

[ft3/s/mi2, cubic feet per second per square mile; e, estimated value; ft3/s, cubic feet per second]

DAY	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
Water Year 2003 (October 2002 to September 2003)												
1	---	---	---	---	---	---	e21	14	20	19	11	8.1
2	---	---	---	---	---	---	e20	14	19	19	9.5	8.4
3	---	---	---	---	---	---	19	12	21	20	9.2	7.5
4	---	---	---	---	---	---	19	13	28	19	9.7	11
5	---	---	---	---	---	---	18	15	26	18	10	8.9
6	---	---	---	---	---	---	16	14	23	17	9.7	7.7
7	---	---	---	---	---	---	20	14	32	17	8.4	7.3
8	---	---	---	---	---	---	19	15	31	16	8.1	7.1
9	---	---	---	---	---	---	25	14	29	16	8	7.9
10	---	---	---	---	---	---	26	14	26	16	7.4	7.6
11	---	---	---	---	---	---	28	14	24	16	7.6	7.2
12	---	---	---	---	---	---	25	14	23	15	7.3	6.9
13	---	---	---	---	---	---	23	13	26	15	7.6	8.7
14	---	---	---	---	---	---	22	13	27	14	9.3	7.8
15	---	---	---	---	---	---	21	13	23	14	8	11
16	---	---	---	---	---	---	21	40	22	14	7.6	11
17	---	---	---	---	---	---	19	29	22	13	11	10
18	---	---	---	---	---	---	19	28	22	14	8.2	12
19	---	---	---	---	---	---	20	26	21	13	7.6	21
20	---	---	---	---	---	---	19	24	33	13	7.2	15
21	---	---	---	---	---	---	18	23	37	12	8.3	13
22	---	---	---	---	---	---	18	22	53	11	9.3	12
23	---	---	---	---	---	---	17	21	33	11	7.7	17
24	---	---	---	---	---	---	17	24	29	12	6.5	12
25	---	---	---	---	---	---	16	25	26	11	6.6	11
26	---	---	---	---	---	---	17	24	24	10	8.4	13
27	---	---	---	---	---	---	16	22	23	10	9.9	14
28	---	---	---	---	---	---	15	22	21	10	8.9	15
29	---	---	---	---	---	---	15	21	20	10	7.7	13
30	---	---	---	---	---	---	15	20	20	9.6	8.6	11
31	---	---	---	---	---	---	---	21	---	9.2	8.1	---
Total	---	---	---	---	---	---	584	598	784	433.8	262.4	323.1
Mean	---	---	---	---	---	---	19.5	19.3	26.1	14	8.46	10.8
Maximum	---	---	---	---	---	---	28	40	53	20	11	21
Minimum	---	---	---	---	---	---	15	12	19	9.2	6.5	6.9
Median	---	---	---	---	---	---	19	20	24	14	8.2	11
ft3/s/mi2	---	---	---	---	---	---	2.18	2.16	2.92	1.56	0.95	1.2
Inches	---	---	---	---	---	---	2.43	2.49	3.26	1.8	1.09	1.34

Appendix 2. Daily mean streamflow in ft3/s measured at the Hopewell Run streamflow-gaging station, Leetown, West Virginia, April 2002 - March 2006.—Continued

[ft3/s/mi2, cubic feet per second per square mile; e, estimated value; ft3/s, cubic feet per second]

DAY	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
Water Year 2004 (October 2003 to September 2004)												
1	11	9.3	14	17	10	18	15	21	11	10	12	6.3
2	11	9.1	13	17	9.8	17	17	21	10	11	e9.5	5.6
3	11	9.3	13	16	11	17	19	22	e11	10	7.5	6.3
4	11	8.9	13	16	11	17	18	19	9.9	11	7.6	6.2
5	11	8.9	14	16	10	16	17	19	24	9.7	7.9	6.5
6	11	9.1	13	15	33	19	16	18	17	9.1	7.8	5.6
7	10	8.9	12	14	37	18	16	17	14	9.2	8	5.4
8	10	8.4	12	15	26	18	15	16	13	9.6	8.3	8.1
9	9.7	8.3	12	14	21	17	15	16	12	8.8	8.2	11
10	9.5	8.3	13	13	21	16	14	15	12	8.7	8.1	7.3
11	9.3	8.3	73	13	20	16	14	15	13	8.8	7.9	7.4
12	9.3	12	30	13	20	15	19	15	14	15	9.1	7.1
13	9.1	11	25	13	19	14	35	14	13	11	11	e6.8
14	11	10	25	13	19	14	33	14	12	8.4	8.8	e6.6
15	13	10	22	13	18	14	26	14	17	8.2	8.7	e6.8
16	10	9.7	21	12	17	15	23	14	23	8	8.6	e6.6
17	11	9.4	20	12	16	14	21	13	17	8	8.8	e6.9
18	11	9.1	19	13	16	14	18	13	15	9.9	8.1	10
19	10	18	18	12	18	15	e17	e24	14	9.2	8.2	e9.6
20	9.7	18	17	12	23	13	17	e22	13	9.1	7.5	e9.0
21	8.7	16	17	11	27	13	17	e20	13	8.6	7.2	e8.6
22	8.5	15	17	11	26	13	16	e17	12	8.6	6.3	e7.8
23	8.5	14	18	11	23	13	20	14	12	8.6	7.1	e7.2
24	8.8	14	27	11	e22	12	21	13	12	7.3	7.2	6.8
25	7.8	15	26	11	e21	13	18	12	11	7	7.4	7.3
26	8.5	14	23	11	20	12	39	e11	11	7	7.3	7.7
27	10	13	21	11	19	12	36	e14	11	7.6	7.4	8.1
28	9.3	15	20	11	19	12	28	11	11	7.5	7.5	36
29	10	15	19	10	18	12	24	e11	10	7.2	7.7	30
30	9.6	14	18	10	---	12	22	e11	10	6.6	8	22
31	9.4	---	18	10	---	12	---	12	---	7.9	7	---
Total	307.7	349	623	396	570.8	453	626	488	397.9	276.6	251.7	286.6
Mean	9.93	11.6	20.1	12.8	19.7	14.6	20.9	15.7	13.3	8.92	8.12	9.55
Maximum	13	18	73	17	37	19	39	24	24	15	12	36
Minimum	7.8	8.3	12	10	9.8	12	14	11	9.9	6.6	6.3	5.4
Median	10	10	18	13	19	14	18	15	12	8.7	7.9	7.2
ft3/s/mi2	1.11	1.3	2.25	1.43	2.2	1.63	2.33	1.76	1.48	1	0.91	1.07
Inches	1.28	1.45	2.59	1.65	2.37	1.88	2.6	2.03	1.65	1.15	1.05	1.19

Appendix 2. Daily mean streamflow in ft3/s measured at the Hopewell Run streamflow-gaging station, Leetown, West Virginia, April 2002 - March 2006.—Continued

[ft3/s/mi2, cubic feet per second per square mile; e, estimated value; ft3/s, cubic feet per second]

DAY	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
Water Year 2005 (October 2004 to September 2005)												
1	18	8.4	11	9.8	9	8.2	25	14	6.8	4.5	4	2.9
2	15	8.3	9.8	9.8	9.1	7.7	40	14	7.1	4.4	4.2	3.2
3	11	8.7	9.6	9.8	9.1	7.8	41	14	7.6	4.2	3.8	3.7
4	9.8	8.4	9.5	9.4	9	7.6	31	12	6.9	4.3	4.9	3.9
5	9.9	6.5	9.2	10	8.8	8	27	11	6.6	4.6	3.8	4
6	9.7	6.4	9.1	9.8	8.7	8.2	26	10	6.5	4.2	4.2	4
7	10	7	9.7	9.5	9	9.3	25	10	6.6	5.2	4.3	3.9
8	9.4	7.7	9.2	9.5	8.8	9.7	25	10	6.3	9.4	3.5	3.8
9	9.6	8.3	12	9.2	8.8	9.3	22	9.6	5.9	5	4.4	3.4
10	9.2	9.5	24	9.2	9.3	9.3	21	8.9	6.3	4.5	4.7	3.7
11	9.2	9.7	21	9.2	8.8	9.4	21	9	6.3	5.8	3.6	4.1
12	9.7	10	18	9.1	8.5	9.3	20	9.4	6.4	4.3	3.6	3.8
13	9.3	9.7	15	9.1	8.5	9.2	19	9.4	7.9	5	3.4	2.5
14	8.2	9.1	15	14	8.6	9.1	19	9.1	8.1	5.6	3.4	3
15	8.5	8.9	14	13	9	8.7	17	9.8	6.8	5.1	3.5	3.6
16	7.9	8.2	14	13	8.6	8.1	16	9.6	6.4	5	3.7	3.8
17	7.8	6.9	13	12	8.5	8.3	16	9.4	6.9	5.4	3.9	3.8
18	8.3	7.6	13	11	8.3	8.4	15	9.3	6.4	4.5	4.9	3.2
19	8	8.1	12	12	8.2	8.4	14	9.1	6.1	3.7	4.3	1.9
20	7.6	8	11	11	8.2	8.7	15	12	6	3.8	3.9	3.8
21	9.6	7.6	12	11	8.5	8.9	15	10	5	5.2	4	3.8
22	8.5	7.8	11	11	8.4	8.5	17	9.6	4.7	4.6	3.8	2.5
23	7.8	8.8	13	11	8.4	19	17	10	4.7	4	3.4	2.6
24	7.9	8	12	10	8.5	19	16	11	4.4	3.7	3.2	2.5
25	7.9	8.5	11	10	8.4	16	17	10	4.2	3.8	3.8	2.6
26	7	8	11	10	8.3	14	15	8.7	4.2	4.2	3.7	3.7
27	7	7.9	11	10	8	15	15	7.3	4.7	3.2	4.4	2.5
28	6.5	9.7	11	9.8	8.5	41	13	7.3	4.8	3.1	3.5	1.8
29	7.1	9.1	11	9.6	---	51	13	7.3	5	3.1	2.9	1.9
30	7.3	8.6	10	9.7	---	33	15	7.1	4.7	3.7	3.4	2.2
31	7.5	---	10	9.2	---	29	---	7	---	3.8	3.8	---
Total	280.2	249.4	382.1	320.7	241.8	427.1	608	304.9	180.3	140.9	119.9	96.1
Mean	9.04	8.31	12.3	10.3	8.64	13.8	20.3	9.84	6.01	4.55	3.87	3.2
Maximum	18	10	24	14	9.3	51	41	14	8.1	9.4	4.9	4.1
Minimum	6.5	6.4	9.1	9.1	8	7.6	13	7	4.2	3.1	2.9	1.8
Median	8.5	8.3	11	9.8	8.6	9.2	17	9.6	6.3	4.4	3.8	3.5
ft3/s/mi2	1.01	0.93	1.38	1.16	0.96	1.54	2.26	1.1	0.67	0.51	0.43	0.36
Inches	1.16	1.04	1.59	1.33	1.01	1.78	2.53	1.27	0.75	0.59	0.5	0.4

Appendix 2. Daily mean streamflow in ft3/s measured at the Hopewell Run streamflow-gaging station, Leetown, West Virginia, April 2002 - March 2006.—Continued

[ft3/s/mi2, cubic feet per second per square mile; e, estimated value; ft3/s, cubic feet per second]

DAY	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
Water Year 2006 (October 2005 to September 2006)												
1	2.6	2.7	6.6	4	5.6	5.4	---	---	---	---	---	---
2	2.9	2.5	5.6	6.3	5.4	5.8	---	---	---	---	---	---
3	2.7	2.5	5	11	7.2	5.6	---	---	---	---	---	---
4	2.7	2.4	5	9	6.6	5.8	---	---	---	---	---	---
5	2.4	2.6	4.7	7.9	6.8	5.7	---	---	---	---	---	---
6	4.3	2.9	4.5	7.3	6.5	5.8	---	---	---	---	---	---
7	6.4	3.1	4.4	6.9	6.3	5.6	---	---	---	---	---	---
8	5.8	3.5	4.4	6.6	6.2	5.6	---	---	---	---	---	---
9	4.7	3.3	5	6.3	6.2	5.3	---	---	---	---	---	---
10	e3.2	3.5	4.5	6.1	6.5	5.9	---	---	---	---	---	---
11	e2.9	4	4.4	6.4	6.7	4.7	---	---	---	---	---	---
12	e2.6	3.4	4.3	6	7.1	5.4	---	---	---	---	---	---
13	e2.6	3.8	4.1	5.7	6.5	5.5	---	---	---	---	---	---
14	e2.8	3.2	4	6.6	6.4	5.5	---	---	---	---	---	---
15	e2.5	4.3	4.2	5.7	6.4	5.3	---	---	---	---	---	---
16	e2.1	3.4	4.7	5.5	6.8	5	---	---	---	---	---	---
17	e2.2	3.2	4.2	5.3	7	4.9	---	---	---	---	---	---
18	e2.1	3.1	4.1	7.6	6.7	4.8	---	---	---	---	---	---
19	e2.0	2.9	4	6.9	6.5	4.8	---	---	---	---	---	---
20	e2.1	2.6	4.1	6.7	6.6	4.7	---	---	---	---	---	---
21	e2.2	3.3	3.9	6.4	6.4	4.7	---	---	---	---	---	---
22	e3.2	4.8	3.9	6.1	6.4	4.8	---	---	---	---	---	---
23	e3.1	3.5	3.9	8.5	6.3	4.5	---	---	---	---	---	---
24	e2.9	3.6	3.9	7.5	6.1	4.3	---	---	---	---	---	---
25	e6.4	3.4	4.8	7.3	6	4.3	---	---	---	---	---	---
26	e6.0	3.3	5.4	6.8	5.9	4.2	---	---	---	---	---	---
27	e4.5	3.3	5	6.6	5.8	4.1	---	---	---	---	---	---
28	3	3.6	4.6	6.6	5.7	4.1	---	---	---	---	---	---
29	2.7	8	4.7	6.5	---	e4.0	---	---	---	---	---	---
30	2.4	8.5	4.4	6.3	---	e4.0	---	---	---	---	---	---
31	3.7	---	4.2	6	---	e3.9	---	---	---	---	---	---
Total	101.7	108.2	140.5	208.4	178.6	154	---	---	---	---	---	---
Mean	3.28	3.61	4.53	6.72	6.38	4.97	---	---	---	---	---	---
Maximum	6.4	8.5	6.6	11	7.2	5.9	---	---	---	---	---	---
Minimum	2	2.4	3.9	4	5.4	3.9	---	---	---	---	---	---
Median	2.8	3.3	4.4	6.6	6.4	4.9	---	---	---	---	---	---
ft3/s/mi2	0.37	0.4	0.51	0.75	0.71	0.56	---	---	---	---	---	---
Inches	0.42	0.45	0.58	0.87	0.74	0.64	---	---	---	---	---	---

Appendix 3. – Water levels in observation wells used in calibration of the ground-water flow model of the Leetown area, West Virginia.

[ft, feet; NAD 83, North American datum of 1983; NAVD 88, North American vertical datum of 1929; NA, not available]

Well name and number	UTM NAD83 easting (ft)	UTM NAD83 northing (ft)	Well depth below land surface (ft)	Elevation of land (ft above NAVD 88)	Water level (ft below land surface)	Water-level elevation (ft above NAVD 88)
Jef-0603 (48)	2412484	315365	475.00	488.74	37.06	451.68
Jef-0599 (44)	2412909	315322	37.50	470.67	15.26	455.41
Jef-0586 (31)	2412909	315332	201.00	470.80	16.53	454.27
Jef-0596 (41)	2414829	315599	101.00	533.04	46.28	486.76
Jef-0587 (32)	2414829	315589	410.00	533.84	46.07	487.77
Jef-0601 (46)	2415951	315214	312.00	531.68	36.22	495.46
Jef-0585 (30)	2415966	315255	326.00	528.65	33.25	495.40
Jef-0592 (37)	2415991	315215	321.00	527.93	32.17	495.76
Jef-0597 (42)	2415967	315234	47.00	528.45	32.53	495.92
Jef-0589 (34)	2417149	315033	260.00	514.99	16.89	498.10
Jef-0598 (43)	2417149	315033	41.50	514.99	15.59	499.40
Jef-0588 (33)	2417663	314789	150.00	510.33	11.69	498.64
Jef-0600 (45)	2417663	314789	79.00	510.33	8.44	501.89
Jef-0602 (47)	2417575	312672	61.00	509.28	7.72	501.56
Jef-0594 (39)	2413523	311194	41.00	492.74	2.37	490.37
Jef-0593 (38)	2414230	311257	56.00	505.76	14.38	491.38
Jef-0595 (40)	2412406	313533	51.00	477.22	19.09	458.13
Jef-0590 (35)	2412406	313543	160.00	476.88	19.77	457.11
Jef-0584 (29)	2412593	313627	93.00	478.66	20.51	458.15
Jef-0591 (36)	2412459	313685	113.00	474.96	18.01	456.95
Jef-0526 (28)	2412645	313810	160.00	480.91	21.75	459.16
Jef-0657 (64)	2416601	314011	4.00	499.76	2.29	497.47
Jef-0658 (65)	2416626	313010	6.00	498.76	1.10	497.66
Jef-0656 (63)	2411306	315345	16.00	452.92	5.97	446.95
Jef-0763 (1)	2406867	313548	82.00	549.71	22.04	527.67
Jef-0764 (2)	2405065	311452	NA	522.28	56.02	466.26
Jef-0765 (3)	2405234	309371	120.00	569.76	18.10	551.66
Jef-0767 (3)	2408724	310645	NA	557.28	16.57	540.71
Jef-0768 (4)	2403106	303303	NA	585.75	30.31	555.44
Jef-0769 (5)	2402460	302928	255.00	551.81	26.70	525.11

Appendix 3. – Water levels in observation wells used in calibration of the ground-water flow model of the Leetown area, West Virginia.—Continued

Well name and number	UTM NAD83 easting (ft)	UTM NAD83 northing (ft)	Well depth below land surface (ft)	Elevation of land (ft above NAVD 88)	Water level (ft below land surface)	Water-level elevation (ft above NAVD 88)
Jef-0770 (6)	2401606	302317	150.00	515.98	26.26	489.72
Jef-0771 (7)	2402089	302588	166.00	527.78	29.91	497.87
Jef-0772 (8)	2402237	302671	266.00	532.61	47.91	484.70
Jef-0773 (9)	2400644	301147	500.00	511.52	64.57	446.95
Jef-0774 (10)	2398972	300521	175.00	498.18	55.26	442.92
Jef-0775 (11)	2399103	298864	250.00	504.35	59.25	445.10
Jef-0776 (12)	2410326	309843	NA	493.09	10.85	482.24
Jef-0777 (13)	2410711	311631	275.00	491.84	28.24	463.60
Jef-0778 (14)	2410451	312143	NA	503.54	38.27	465.27
Jef-0779 (15)	2414056	297847	212.00	606.75	69.45	537.30
Jef-0780 (16)	2414326	298610	195.00	573.15	37.43	535.72
Jef-0781 (17)	2416907	304666	NA	597.59	56.19	541.40
Jef-0782 (18)	2415423	304600	182.00	555.59	33.23	522.36
Jef-0784 (20)	2414564	302025	NA	548.81	21.83	526.98
Jef-0785 (21)	2414769	301563	300.00	559.66	32.81	526.85
Jef-0579 (22)	2414056	299182	205.00	566.64	32.13	534.51
Jef-0786 (23)	2407309	300229	518.00	562.32	50.23	512.09
Jef-0787 (24)	2398937	305378	NA	518.21	68.15	450.06
Jef-0788 (25)	2399702	305714	150.00	527.96	74.46	453.50
Jef-0789 (26)	2399352	307307	625.00	501.39	55.60	445.79
Jef-0790 (27)	2401019	311403	125.00	423.85	20.69	403.16
Jef-0629 (55)	2410482	312163	162.00	503.27	35.72	467.55
Jef-0630 (56)	2418033	310768	80.00	542.50	29.26	513.24
Jef-0627 (54)	2415740	316030	51.00	517.60	22.36	495.24
Jef-0626 (53)	2413394	317668	416.00	495.62	39.15	456.47
Jef-0623 (52)	2416799	315714	135.00	536.87	39.40	497.47
Jef-0622 (51)	2417651	308828	95.42	583.37	57.56	525.81
Jef-0619 (50)	2420485	307634	375.00	610.28	43.15	567.13
Jef-0606 (49)	2415180	309918	64.00	522.00	18.55	503.45
Jef-0639 (57)	2416175	316361	275.00	523.28	22.55	500.73

Appendix 3. – Water levels in observation wells used in calibration of the ground-water flow model of the Leetown area, West Virginia.—Continued

Well name and number	UTM NAD83 easting (ft)	UTM NAD83 northing (ft)	Well depth below land surface (ft)	Elevation of land (ft above NAVD 88)	Water level (ft below land surface)	Water-level elevation (ft above NAVD 88)
Jef-0642 (58)	2415358	316347	74.00	515.40	17.00	498.40
Jef-0643 (59)	2412183	311454	45.00	498.22	22.55	475.67
Jef-0645 (60)	2415907	315952	187.00	514.35	14.81	499.54
Jef-0701 (81)	2417981	308379	53.06	578.70	38.62	540.08
Jef-0673 (70)	2418865	309922	33.93	566.30	16.01	550.29
Jef-0702 (82)	2419128	308389	66.44	599.79	46.59	553.20
Jef-0667 (69)	2417906	310432	105.44	536.84	19.12	517.72
Jef-0666 (68)	2418571	310130	75.01	570.93	39.41	531.52
Jef-0665 (67)	2417987	310281	38.03	541.75	22.54	519.21
Jef-0683 (73)	2412014	316217	250.00	510.31	40.58	469.73
Jef-0684 (74)	2415014	317575	213.00	546.08	57.05	489.03
Jef-0692 (77)	2415257	312702	39.43	514.36	24.95	489.41
Jef-0691 (76)	2412445	310852	29.20	502.87	20.90	481.97
Jef-0690 (75)	2414359	316845	390.00	520.53	50.03	470.50
Jef-0697 (80)	2413676	316833	435.00	502.51	37.98	464.53
Jef-0696 (79)	2414829	319606	572.00	499.11	30.03	469.08
Jef-0694 (78)	2417697	310256	184.00	555.12	40.36	514.76
Jef-0679 (71)	2415367	310478	140.00	538.45	38.26	500.19
Jef-0681 (72)	2417576	308625	205.00	576.63	53.34	523.29
Jef-0660 (66)	2419247	314523	115.00	562.36	40.47	521.89
Jef-0652 (62)	2415632	315927	50.00	517.19	18.38	498.81
Jef-0651 (61)	2411613	312588	62.00	471.88	8.85	463.03
Jef-0744 (83)	2412340	314199	48.00	462.17	10.48	451.69

Appendix 4. Precipitation at Gray Spring at Leetown, West Virginia, November 2002 - September 2005

[All values are in inches; e, estimated value; ---, no data available].

DAY	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
October 2002 - September 2003												
1.00	---	e0.01	0.00	e1.33	e0.06	e0.00	0.00	0.01	0.03	0.00	0.38	0.06
2.00	---	0.00	0.00	e0.08	e0.00	e0.17	0.00	0.00	0.00	0.05	0.00	0.27
3.00	---	0.00	0.00	e0.31	e0.01	e0.01	0.00	0.00	0.69	0.32	0.00	0.03
4.00	---	0.00	0.00	e0.00	e0.32	e0.00	0.00	0.10	0.32	0.00	0.39	0.72
5.00	---	0.58	e0.72	e0.23	e0.00	e0.00	0.01	0.22	0.01	0.00	0.00	0.00
6.00	---	0.02	e0.01	e0.03	e0.09	e0.29	0.00	0.00	0.00	0.29	0.00	0.00
7.00	---	0.00	e0.01	e0.00	e0.21	e0.00	0.61	0.16	0.78	0.22	0.00	0.00
8.00	---	0.00	e0.00	e0.00	e0.00	e0.00	0.00	0.27	0.09	0.04	0.19	0.00
9.00	---	0.00	e0.00	e0.00	e0.00	e0.00	0.49	0.28	0.04	0.22	0.00	0.00
10.00	---	0.00	e0.00	e0.01	e0.01	e0.00	0.01	0.13	0.00	0.07	0.00	0.00
11.00	---	0.31	e1.24	0.00	e0.03	e0.01	0.18	0.02	0.01	0.00	0.04	0.00
12.00	---	0.63	e0.00	0.00	e0.01	e0.00	0.00	0.00	0.32	0.18	0.00	0.13
13.00	---	0.00	e0.50	e0.00	e0.00	e0.18	0.00	0.00	0.44	0.00	0.00	0.35
14.00	---	0.00	0.05	e0.01	e0.00	e0.00	0.00	0.00	0.00	0.00	0.00	0.04
15.00	---	0.00	0.00	e0.01	e0.21	e0.00	0.00	e0.18	0.01	0.00	0.00	0.77
16.00	---	0.53	e0.01	e0.14	e1.16	e0.00	0.00	e0.42	0.00	0.02	0.97	0.00
17.00	---	0.44	0.00	e0.05	e0.44	e0.00	0.00	e0.10	0.19	0.00	0.30	0.00
18.00	---	0.00	0.00	e0.01	e0.02	e0.00	0.19	e0.14	0.03	0.00	0.00	1.10
19.00	---	0.03	e0.01	e0.00	e0.01	e0.00	0.09	e0.01	0.22	0.00	0.01	0.18
20.00	---	0.00	e0.15	e0.01	e0.00	e1.57	0.00	e0.00	0.42	0.00	0.00	0.00
21.00	---	0.46	0.00	e0.01	e0.25	e0.02	0.12	e0.07	0.65	0.00	0.00	0.00
22.00	---	0.00	0.00	e0.00	e1.09	e0.00	0.06	e0.01	0.00	0.01	0.74	0.21
23.00	---	0.00	0.00	e0.01	e0.16	e0.00	0.00	e0.15	0.00	0.46	0.00	0.53
24.00	---	0.00	e0.19	e0.00	e0.00	e0.00	0.00	e0.16	0.00	0.00	0.00	0.00
25.00	---	0.00	e0.31	e0.00	e0.00	e0.00	0.11	0.00	0.00	0.00	0.00	0.25
26.00	---	0.04	e0.00	e0.01	e0.14	e0.30	0.03	0.10	0.00	0.00	0.83	0.00
27.00	---	0.05	e0.00	e0.00	e0.23	e0.00	0.00	0.00	0.00	0.00	0.51	0.48
28.00	---	0.00	e0.00	e0.00	e0.05	0.00	0.00	0.22	0.00	0.14	0.00	0.04
29.00	---	0.00	e0.00	e0.01	---	0.03	0.06	0.02	0.00	0.01	0.00	0.00
30.00	---	0.00	e0.02	e0.02	---	e0.57	0.00	0.00	0.17	0.00	0.06	0.00
31.00	---	---	e0.00	e0.12	---	e0.01	---	0.43	---	0.03	0.00	---
TOTAL	---	3.10	3.22	2.40	4.50	3.16	1.96	3.20	4.42	2.06	4.42	5.16
MEAN	---	0.10	0.10	0.08	0.16	0.10	0.07	0.10	0.15	0.07	0.14	0.17
MEDIAN	---	0.00	0.00	0.01	0.03	0.00	0.00	0.07	0.01	0.00	0.00	0.01

Appendix 4. Precipitation at Gray Spring at Leetown, West Virginia, November 2002 - September 2005—Continued

[All values are in inches; e, estimated value; ---, no data available].

DAY	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
October 2003 - September 2004												
1.00	0.06	0.00	0.00	0.00	0.02	0.00	0.63	0.02	0.02	0.23	0.01	0.00
2.00	0.00	0.00	0.00	0.10	0.10	0.00	0.40	0.64	0.01	0.00	0.00	0.00
3.00	0.00	0.00	0.00	0.00	e1.03	0.00	0.01	0.00	0.01	0.00	0.00	0.00
4.00	0.15	0.00	0.00	0.00	e0.00	0.03	0.01	0.00	0.02	0.54	0.00	0.00
5.00	0.00	0.18	e0.60	0.07	e0.23	0.00	0.00	0.00	1.85	0.01	0.00	0.01
6.00	0.00	0.17	0.00	0.00	e1.98	0.41	0.00	0.00	0.00	0.00	0.00	0.02
7.00	0.00	0.00	0.05	0.00	e0.00	0.06	0.00	0.06	0.00	0.29	0.00	0.03
8.00	0.00	0.00	0.10	0.00	e0.00	0.00	0.03	0.00	0.00	0.00	0.00	1.46
9.00	0.00	0.00	0.17	0.00	e0.00	0.00	0.00	0.00	0.00	0.00	0.88	0.18
10.00	0.00	0.00	1.08	0.00	e0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.00
11.00	0.00	0.00	0.52	0.00	0.00	0.00	0.04	0.00	0.82	0.00	0.37	0.00
12.00	0.00	0.68	0.00	0.00	e0.00	0.00	1.14	0.00	0.00	1.83	0.78	0.00
13.00	0.00	0.01	0.00	0.00	e0.00	0.00	0.39	0.00	0.13	0.13	0.05	0.00
14.00	0.99	0.00	e0.86	0.00	0.00	e0.02	0.00	0.28	0.02	0.01	0.00	0.16
15.00	0.00	0.00	0.06	0.00	e0.00	0.00	0.00	0.12	1.16	0.00	0.00	0.17
16.00	0.00	0.00	0.15	0.00	e0.00	e0.23	0.00	0.00	0.00	0.00	0.00	0.00
17.00	0.13	0.00	0.12	e0.07	e0.00	0.00	0.00	0.00	0.01	0.00	0.00	1.46
18.00	0.00	0.00	0.00	0.24	e0.00	0.18	0.00	0.45	0.00	0.50	0.00	0.13
19.00	0.00	1.20	0.05	0.00	e0.00	0.06	0.00	0.36	0.00	0.00	0.06	0.00
20.00	0.00	0.00	0.05	0.00	e0.01	0.09	0.03	0.00	0.00	0.00	0.08	0.00
21.00	0.00	0.00	0.02	0.00	e0.01	0.01	0.01	0.62	0.00	0.00	0.04	0.00
22.00	0.03	0.00	0.02	0.00	e0.00	0.00	0.00	0.01	0.00	0.21	0.00	0.00
23.00	0.00	0.00	0.00	e0.06	e0.00	0.00	1.19	0.01	0.00	0.40	0.00	0.00
24.00	0.00	0.39	0.35	e0.20	0.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00
25.00	0.00	0.00	0.00	e0.38	0.00	0.01	0.16	0.00	0.06	0.01	0.00	0.00
26.00	0.05	0.00	0.00	e0.31	e0.00	0.00	1.09	0.11	0.01	0.00	0.00	0.00
27.00	0.56	0.00	0.00	e0.18	e0.00	0.02	0.00	0.02	0.00	0.09	0.00	0.02
28.00	0.03	0.40	0.00	0.01	0.00	0.00	0.00	0.08	0.00	0.00	0.00	2.83
29.00	0.26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.00
30.00	0.00	0.00	0.01	0.00	---	0.08	0.00	0.01	0.00	0.00	0.00	0.00
31.00	0.00	---	0.00	0.00	---	0.01	---	0.09	---	1.07	0.00	---
TOTAL	2.26	3.03	4.21	1.62	3.52	1.21	5.13	2.88	4.16	5.36	2.27	6.47
MEAN	0.07	0.10	0.14	0.05	0.12	0.04	0.17	0.09	0.14	0.17	0.07	0.22
MEDIAN	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Appendix 4. Precipitation at Gray Spring at Leetown, West Virginia, November 2002 - September 2005—Continued

[All values are in inches; e, estimated value; ---, no data available].

DAY	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
						October 2004 - September 2005						
1.00	0.00	0.00	0.31	e0.00	0.00	e0.01	0.12	0.00	0.00	0.00	0.00	0.00
2.00	0.02	0.00	0.00	e0.00	0.00	e0.00	0.81	0.01	0.00	0.00	0.00	0.00
3.00	0.00	0.00	0.00	e0.01	e0.16	0.00	0.00	0.00	0.15	0.00	0.00	0.00
4.00	0.00	0.64	0.00	e0.02	e0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
5.00	0.00	0.00	0.00	e0.49	0.00	0.00	0.00	0.00	0.00	0.26	0.00	0.00
6.00	0.00	0.00	0.01	e0.01	0.00	0.00	0.00	0.00	0.25	0.00	0.00	0.00
7.00	0.00	0.00	0.27	e0.05	0.00	0.00	0.08	0.00	0.00	0.37	0.00	0.00
8.00	0.00	0.00	0.00	e0.19	0.00	0.17	0.07	0.00	0.00	1.30	0.12	0.00
9.00	0.00	0.00	0.86	e0.00	0.07	0.00	0.00	0.00	0.00	0.00	0.50	0.00
10.00	0.00	0.00	0.64	e0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11.00	0.00	0.00	0.00	e0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12.00	0.00	0.97	0.00	e0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13.00	0.12	0.00	0.00	e0.03	0.00	0.00	0.00	0.00	0.60	0.59	0.00	0.00
14.00	0.35	0.00	0.00	e0.92	e0.32	0.00	0.00	0.25	0.00	0.00	0.00	0.00
15.00	0.03	0.00	0.00	e0.00	e0.00	0.00	0.00	0.15	0.00	0.08	0.00	0.00
16.00	0.06	0.00	0.00	e0.00	e0.02	0.00	0.00	0.00	0.00	0.40	0.00	0.02
17.00	0.00	0.00	0.00	e0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
18.00	0.02	0.01	0.00	e0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
19.00	0.22	0.06	0.00	e0.00	0.00	0.00	0.00	0.07	0.00	0.00	0.40	0.00
20.00	0.52	0.01	0.00	e0.00	e0.06	e0.02	0.00	0.77	0.00	0.00	0.00	0.00
21.00	0.04	0.01	0.00	e0.00	e0.04	0.00	0.03	0.09	0.00	0.43	0.00	0.00
22.00	0.03	0.00	0.00	e0.17	0.00	e0.01	0.37	0.00	0.36	0.00	0.00	0.00
23.00	0.00	0.00	0.49	e0.00	0.00	e1.73	0.19	0.26	0.00	0.00	0.00	0.00
24.00	0.11	0.21	0.00	e0.00	0.00	0.01	0.00	0.17	0.00	0.00	0.00	0.00
25.00	0.01	0.21	0.00	e0.00	0.37	0.00	0.00	0.04	0.00	0.08	0.00	0.00
26.00	0.00	0.00	0.00	e0.00	0.02	e0.14	0.00	0.00	0.00	0.00	0.00	0.02
27.00	0.00	0.02	0.00	0.00	0.00	e0.49	0.00	0.00	0.00	0.00	0.33	0.00
28.00	0.00	0.39	0.00	0.00	e0.36	e1.75	0.00	0.05	0.00	0.00	0.01	0.00
29.00	0.06	0.00	0.00	e0.06	---	0.11	0.00	0.00	0.01	0.00	0.00	0.01
30.00	0.00	0.12	0.00	e0.09	---	0.00	0.46	0.13	0.00	0.00	0.81	0.00
31.00	0.00	---	---	0.00	---	0.00	---	0.00	---	0.00	0.01	---
TOTAL	1.59	2.65	2.58	2.05	1.43	4.45	2.13	1.99	1.37	3.51	2.18	0.05
MEAN	0.05	0.09	0.09	0.07	0.05	0.14	0.07	0.06	0.05	0.11	0.07	0.00
MEDIAN	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00