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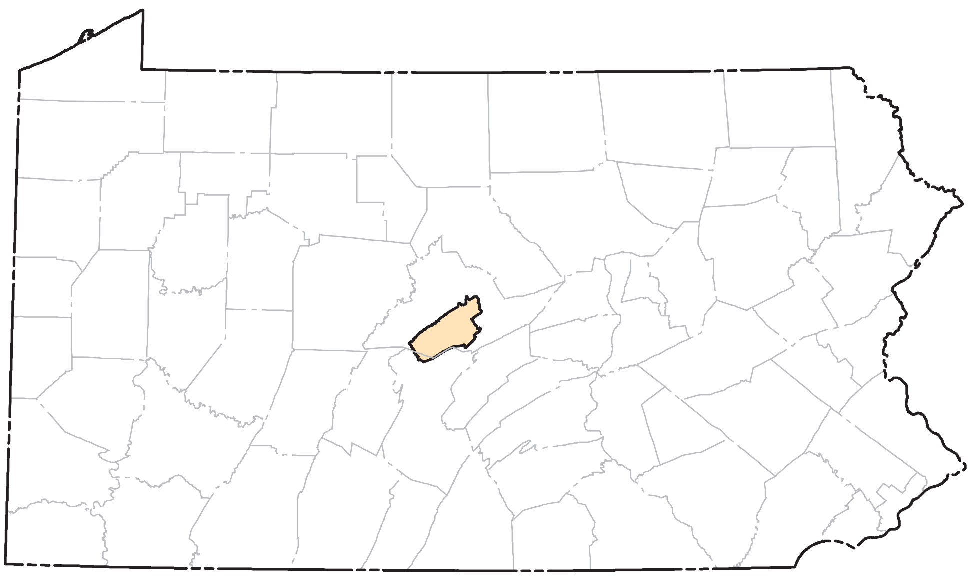

Scientific Investigations Report 2015–5073

U.S. Department of the Interior
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Cover. Map showing location of study area.

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SALLY JEWELL, Secretary

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

U.S. Geological Survey, Reston, Virginia: 2015

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Conversion Factors

[Inch/Pound to International System of Units[

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
square foot (ft^2)	0.09290	square meter (m^2)
square inch (in^2)	6.452	square centimeter (cm^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	0.003785	cubic meter (m^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
cubic inch (in^3)	16.39	cubic centimeter (cm^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
foot per second (ft/s)	0.3048	meter per second (m/s)
foot per day (ft/d)	0.3048	meter per day (m/d)
foot per year (ft/yr)	0.3048	meter per year (m/yr)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile [(ft^3/s)/mi^2]	0.01093	cubic meter per second per square kilometer [(m^3/s)/km^2]
gallon per minute (gal/min)	0.06309	liter per second (L/s)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
	Pressure	
atmosphere, standard (atm)	101.3	kilopascal (kPa)
inch of mercury at 60ºF (in Hg)	3.377	kilopascal (kPa)
pound per square inch (lb/in^2)	6.895	kilopascal (kPa)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as:

$$°F = (1.8 \times °C) + 32.$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as:

$$°C = (°F - 32) / 1.8.$$

Datum

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).

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

Abbreviations

CWC	ClearWater Conservancy
DEM	digital elevation model
EPA	U.S. Environmental Protection Agency
ET	evapotranspiration
GIS	geographic information system
GSFLOW	Groundwater and Surface-water FLOW
HRU	hydrologic response unit
IDE	Inverse Distance and Elevation
MISTE	MIssing STreamflow Estimation
MODFLOW-NWT	Modular Groundwater Flow Model
NED	National Elevation Dataset
NHD	National Hydrography Dataset
PADEP	Pennsylvania Department of Environmental Protection
PEST	Parameter ESTimation
PRMS	Precipitation-Runoff Modeling System
RMSD	root mean squared difference
SSURGO	Soil Survey Geographic Database
SCWC	Spring Creek Watershed Committee
SRBC	Susquehanna River Basin Commission
USGS	U.S. Geological Survey
UTM	Universal Transverse Mercator
VSA	variable source area

Water-Budget and Recharge-Area Simulations for the Spring Creek and Nittany Creek Basins and Parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania, Water Years 2000–06

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Abstract

This report describes the results of a study by the U.S. Geological Survey in cooperation with ClearWater Conservancy and the Pennsylvania Department of Environmental Protection to develop a hydrologic model to simulate a water budget and identify areas of greater than average recharge for the Spring Creek Basin in central Pennsylvania. The model was developed to help policy makers, natural resource managers, and the public better understand and manage the water resources in the region. The Groundwater and Surface-water FLOW model (GSFLOW), which is an integration of the Precipitation-Runoff Modeling System (PRMS) and the Modular Groundwater Flow Model (MODFLOW-NWT), was used to simulate surface water and groundwater in the Spring Creek Basin for water years 2000–06. Because the groundwater and surface-water divides for the Spring Creek Basin do not coincide, the study area includes the Nittany Creek Basin and headwaters of the Spruce Creek Basin.

The hydrologic model was developed by the use of a stepwise process: (1) develop and calibrate a PRMS model and steady-state MODFLOW-NWT model; (2) re-calibrate the steady-state MODFLOW-NWT model using potential recharge estimates simulated from the PRMS model, and (3) integrate the PRMS and MODFLOW-NWT models into GSFLOW. The individually calibrated PRMS and MODFLOW-NWT models were used as a starting point for the calibration of the fully coupled GSFLOW model. The GSFLOW model calibration was done by comparing observations and corresponding simulated values of streamflow from 11 streamgages and groundwater levels from 16 wells.

The cumulative water budget and individual water budgets for water years 2000–06 were simulated by using GSFLOW. The largest source and sink terms are represented by precipitation and evapotranspiration, respectively. For the period simulated, a net surplus in the water budget was computed where inflows exceeded outflows by about 1.7 billion cubic feet (0.47 inches per year over the basin area); storage increased by about the same amount to balance the budget.

The rate and distribution of recharge throughout the Spring Creek, Nittany Creek, and Spruce Creek Basins is variable as a result of the high degree of hydrogeologic heterogeneity and karst features. The greatest amount of recharge was simulated in the carbonate-bedrock valley, near the toe slopes of Nittany and Tussey Mountains, in the Scotia Barrens, and along the area coinciding with the Gatesburg Formation.

Runoff extremes were observed for water years 2001 (dry year) and 2004 (wet year). Simulated average recharge rates (water reaching the saturated zone as defined in GSFLOW) for 2001 and 2004 were 5.4 in/yr and 22.0 in/yr, respectively. Areas where simulations show large variations in annual recharge between wet and dry years are the same areas where simulated recharge was large. Those areas where rates of groundwater recharge are much higher than average, and are capable of accepting substantially greater quantities of recharge during wet years, might be considered critical for maintaining the flow of springs, stream base flow, or the source of water to supply wells. The slopes of the Bald Eagle, Tussey, and Nittany Mountains are relatively insensitive to variations in recharge, primarily because of reduced infiltration rates and steep slopes.

Introduction

The Spring Creek Basin, Nittany Creek Basin, and headwaters of the Spruce Creek Basin in central Pennsylvania (collectively termed the “study basin”) have experienced growth and development resulting in land-use change and increased water use in parts of the basins. These changes influence the (1) quantity and availability of surface water and groundwater, (2) surface-water and groundwater interactions, and (3) aquatic resources in the basin. The study basin was identified as one of seven potentially stressed areas in the Susquehanna

River Basin because of stormwater issues, groundwater contamination, mine dewatering, and diminished streamflow caused by groundwater withdrawals (Susquehanna River Basin Commission, 2005, p. 18–20). To assist water-management agencies in assessing the effects of increased water use and land-use change on surface-water and groundwater resources, the U.S. Geological Survey (USGS) in cooperation with ClearWater Conservancy (CWC) and the Pennsylvania Department of Environmental Protection (PADEP) developed a computer simulation model of the groundwater and surface-water system by using the coupled groundwater and surface-water flow model GSFLOW (Markstrom and others, 2008). Because of the variability in hydrologic connectivity between surface-water and groundwater across the study area, a model capable of simulating interactions between the systems was needed. GSFLOW is a useful tool (Mejia and others, 2012; Huntington and Niswonger, 2012) for assessing the effects of land-use change on surface-water and groundwater resources.

Purpose and Scope

This report describes the development of a GSFLOW computer model and presents the climate, physiographic, geologic, land-use, hydrologic, and streamflow data used to drive the computer model. The data were used to develop a model of the hydrology of the study area capable of accounting for water through the land surface, soils, subsurface, and stream network. Calibration of the model is discussed, and results of the simulations are presented.

The specific objectives of this project were to (1) establish a water budget for the study basin using GSFLOW for water years[1] 2000–06 and (2) identify areas of greater than average recharge that can be used to assist decision makers in managing water resources. By documenting the steps needed to develop a GSFLOW model, the approach described in this report could be used to develop a baseline water budget and to estimate water volume and distribution for various uses or processes, such as drinking water, surface-water runoff, streamflow, and ecological flows for other basins in the Commonwealth of Pennsylvania.

Previous Studies

Substantive investigations related to the study basin are referenced in Fulton and others (2005), who summarize the hydrologic and physical characteristics of the basins and present a conceptual model for surface-water and groundwater flow. The data and the conceptual model reported by Fulton and others (2005) were used to demonstrate the need for a coupled-regions model, which dynamically accounts for the spatial and temporal distribution of surface water and groundwater.

Study Area

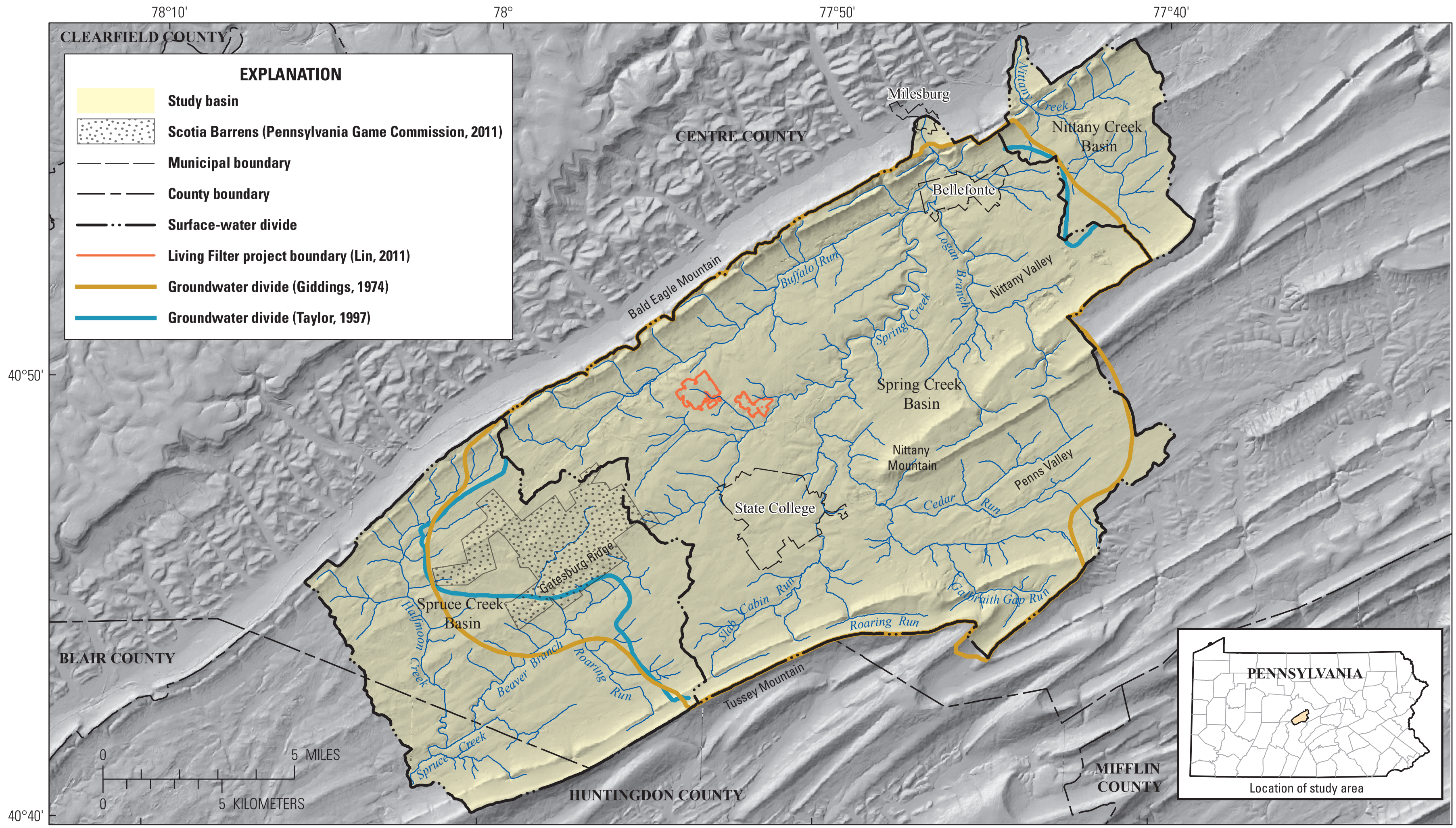
The study basin is 229 square miles (mi^2) in Centre and Huntingdon Counties in central Pennsylvania (fig. 1). The study basin incorporates all of Spring Creek and Nittany Creek Basins and the headwaters of the Spruce Creek Basin. The study basin is equivalent to the domain of the GSFLOW model. The Spring Creek Basin is 147 mi^2, the Nittany Creek Basin is 17 mi^2, and the headwaters of Spruce Creek Basin in the study area is about 65 mi^2. The study basin is divided into 14 subbasins in the GSFLOW model (fig. 2).

Water-level maps indicate that groundwater and surface-water divides do not coincide in the study area (Giddings, 1974; Taylor, 1997). The Spring Creek groundwater basin is approximately 175 mi^2 (Fulton and others, 2005), which is about 28 mi^2 larger than the Spring Creek surface-water basin. The study basin includes the groundwater divide that delineates the area of groundwater contribution to the Spring Creek Basin (fig. 1). The contributing area for groundwater flow from Nittany and Spruce Creek Basins, which is captured by Spring Creek, is not a fixed area; thus, it may vary based on hydrologic conditions and nearby groundwater withdrawals (Brachet, 2004).

Two principal hydrologic settings define the study area—a forested, siliciclastic (sandstone and shale) -bedrock upland and a carbonate (limestone and dolomite) -bedrock valley with agricultural, suburban, and urban land uses. The settings differ in physiography, geology, and land use but are linked hydrologically by climate, evapotranspiration, surface runoff, interflow, snowmelt, recharge, and groundwater flow from the uplands, which provide and limit the water available for streamflow and groundwater recharge and discharge within the valley.

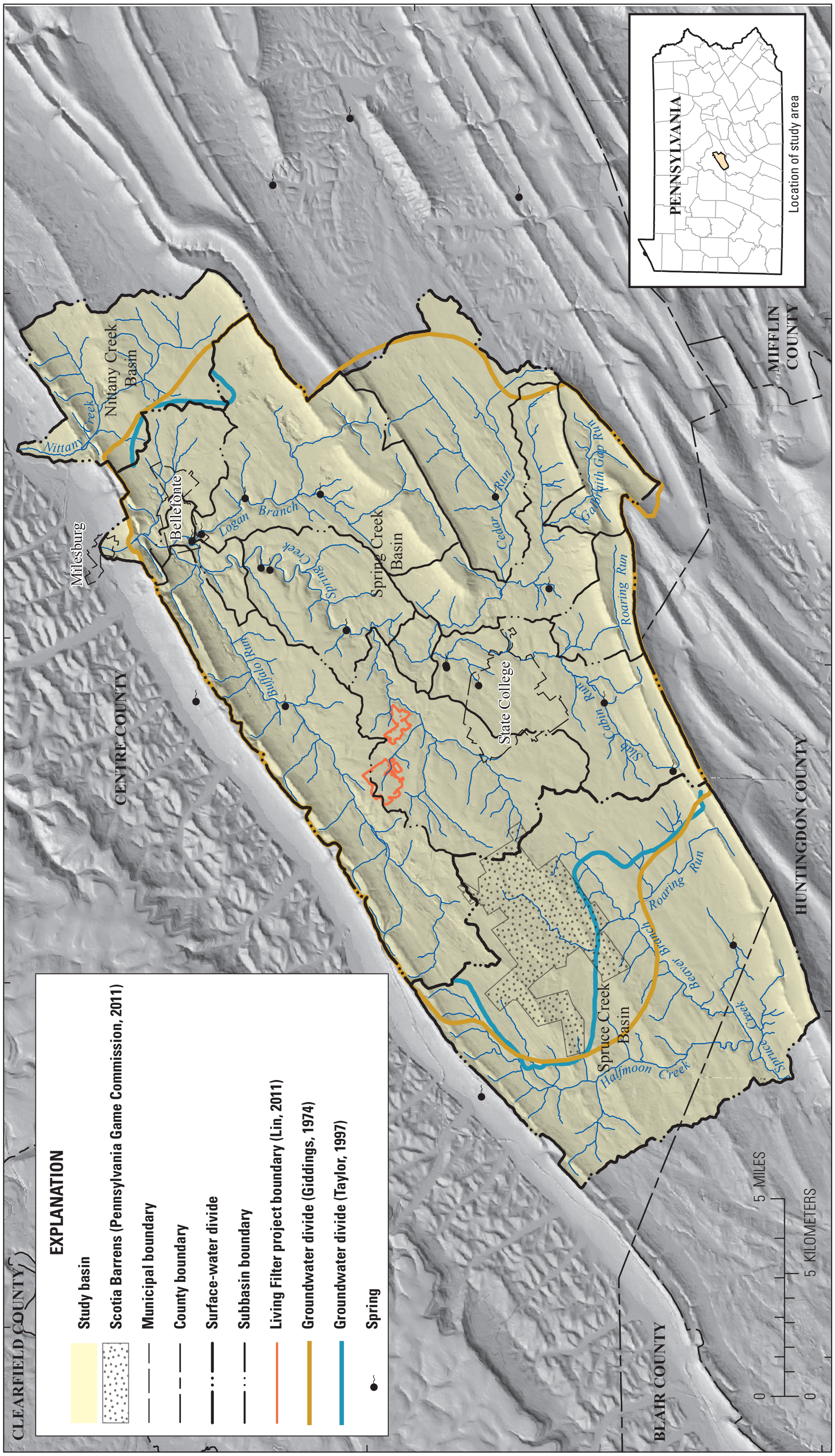
Forested, siliciclastic-bedrock uplands bound the study basin to the north and south. The carbonate-bedrock valley is dominated by agricultural and urban land uses and is described by Fulton and others (2005). Direct runoff from upland subbasins is characterized by variable source-area (VSA) hydrology, which is common in well-vegetated, humid areas that contain thin soil layers with large infiltration capacities and laterally continuous, low-permeability zones (Fulton and others, 2005). The carbonate-bedrock units in the valley are highly fractured and contain sinkholes and conduits, which promote rapid recharge and streamflow response to precipitation and snowmelt events and influence the rate and direction of groundwater flow. However, in areas where the residual soil veneer is substantial (greater than 100 feet), wetting fronts are attenuated, and the water-table response to precipitation and snowmelt can be delayed. The carbonate-bedrock units are capable of providing groundwater to wells that withdraw in excess of 1 million gallons of water per day (Fulton and others, 2005). Groundwater in the carbonate-bedrock units ultimately discharges to streams, large springs, wells, and mines, and as evapotranspiration to riparian vegetation.

[1] A water year is the 12-month period that begins October 1 and ends September 30. It is designated by the year in which it ends.



Base from U.S. Geological Survey digital data, 1972
Universal Transverse Mercator projection, Zone 18, NAD 1983
Streams from U.S. Geological Survey, National Hydrography Dataset, 2009
Shaded relief from PAMAP Program, 2008

Figure 1. Location of Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania.



Base from U.S. Geological Survey digital data, 1972
Universal Transverse Mercator projection, Zone 18, NAD 1983
Streams from U.S. Geological Survey, National Hydrography Dataset, 2009
Shaded relief from PAMAP Program, 2008

Figure 2. Delineation of subbasins in Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania.

Groundwater recharge typically is greatest during November through May when evapotranspiration rates are minimal. Recharge to the carbonate-bedrock aquifer occurs along six pathways as conceptualized by Parizek (1984): (1) direct infiltration of precipitation into soils and exposed bedrock; (2) concentrated stormwater runoff from the valley into sinkholes; (3) concentrated surface runoff from uplands into sinkholes; (4) diffuse surface runoff from uplands; (5) streamflow losses from perched or intermittent streams on karst terrain; and (6) leakage from underground pipes, disposal of on-lot sewage effluent, and irrigation.

Simulation Methods and the GSFLOW Model

To simulate the hydrologic cycle, a modified version of GSFLOW (Markstrom and others, 2008; enhanced version 1.1.5) was used in the model domain. It is a physically based, distributed model that simulates coupled groundwater and surface-water flow across the land surface, in the stream network, and within the subsurface variably saturated and saturated materials in single or multiple basins (Markstrom and others, 2008). GSFLOW simulates the timing, feedback, and rates of exchange of water and energy in the atmosphere, canopy, snowpack, pervious and impervious areas of the land surface, soil, unsaturated and saturated zones, streams, lakes, and the effects of wells and surface-water diversions using daily time series climate and water-use data.

The version of GSFLOW (enhanced version 1.1.5) used for this project includes the Newton solution method and the Inverse Distance and Elevation (IDE) module. The Newton solution method is a formulation of MODFLOW-2005, designed to solve problems involving drying and rewetting in hydrogeologic settings, which are dominated by nonlinearity. This feature is particularly important to the study basin, which is characterized by unconfined conditions, steep topography, and surface-water/groundwater interactions.

IDE uses a combination of inverse distance and elevation weighting to interpolate maximum and minimum precipitation and temperature data for each hydrologic response unit (HRU) in the PRMS model. HRUs are spatial discretizations of the land surface, which are commonly represented as polygons or cascading-flow networks to stream segments and possess similar parameters, such as soil type, land cover, land use, and geology.

Model Overview

GSFLOW integrates two previously documented USGS models—the Precipitation Runoff Modeling System (PRMS) and the three-dimensional, modular groundwater-flow model MODFLOW-NWT (Niswonger and others, 2011). PRMS simulates the distribution of water from the top of the plant canopy to the bottom of the soil zone on the basis of hydrologic and climate variables, such as precipitation, air temperature, potential solar radiation, and evapotranspiration. MODFLOW-NWT simulates the distribution of water from the base of the soil zone, through the unsaturated zone, to the saturated zone, and the discharges of water to streams and the land surface. GSFLOW couples these models within the soil veneer on the basis of soil moisture content, hydrogeologic characteristics, and hydraulic-head differences.

Surface-water/groundwater interactions can occur between the (1) PRMS simulated soil zone and MODFLOW-NWT simulated unsaturated zone, (2) PRMS simulated surface runoff and shallow lateral subsurface flow (interflow) to MODFLOW-NWT simulated streams and lakes, and (3) MODFLOW-NWT simulated unsaturated and saturated flow in subsurface areas below the soil zone to streams and lakes. The governing equations of each region are solved separately in an iterative process to balance the dependent variables and conserve mass throughout the model. Flow in the unsaturated-zone beneath the soil zone, streams, and lakes is based on a one-dimensional kinematic-wave approximation to the Richards equation solved by using the UZF Package within MODFLOW-NWT (Niswonger and others, 2007). Streamflow routing is simulated by using the Streamflow Routing Package within MODFLOW-NWT (Niswonger and Prudic, 2005).

The states and fluxes among the soil zone, unsaturated zone, and saturated zone are available to compute a water budget and components of flow in and out of each spatial unit: (1) HRUs, (2) MODFLOW-NWT cells, (3) stream segments, (4) intersection of HRUs and MODFLOW-NWT cells, and (5) intersections between stream segments and MODFLOW-NWT cells or reaches. These spatial units are connected topologically such that simulated flows cascade on the basis of hydrologic gradients. Hydrologic processes are simulated by using a daily time step, and a water budget can be generated by region or stream segment, and for specified time period.

Model Development

Model development involved a three-step process: (1) develop and calibrate a PRMS model and steady-state MODFLOW-NWT model; (2) re-calibrate the steady-state MODFLOW-NWT model using potential recharge estimates simulated from the PRMS-only model, and (3) integrate the PRMS and MODFLOW-NWT models in the GSFLOW structure and calibrate the coupled model using the individually calibrated PRMS and MODFLOW-NWT models as a starting point. This calibration process was an iterative process occurring as new information and enhancements to GSFLOW were added to improve the model. Calibration was accomplished by comparing observed streamflow and groundwater levels to simulated values with a combination of best professional judgment, manual adjustment of model parameters, and automated methods including Parameter Estimation (PEST) (Doherty and Hunt, 2010). Model development is illustrated schematically in figure 3. Note that the MODFLOW-NWT model was calibrated for steady-state conditions (step 1); initial adjustments of aquifer properties were done with a model constructed with a uniform spatial distribution of infiltration, then was recalibrated by using spatially variable estimates of infiltration from the PRMS model output (step 2). The infiltration of water below the root zone simulated by PRMS has been used as input for MODFLOW models in various applications (Bjerklie and others, 2010; Jeton and Maurer, 2007; Lee and Risley, 2001; Steuer and Hunt, 2001; Hunt and Steuer, 2000; Vaccaro, 1992; and Ely and others, 2011). The simulated rate of infiltration below the root zone in PRMS-only can be thought of as potential recharge that will either be added to the saturated zone or be rejected by MODFLOW-NWT.

PRMS-Only Model Development

An overview of the development of the PRMS model is described in the following section. The digital elevation model (DEM) developed for the PRMS, the modeled area, HRU delineation, HRU cascades, HRU parameterization, climate data, calibration, and results prior to running GSFLOW are discussed.

Overview

PRMS (Leavesley and others, 1983; Leavesley and Stannard, 1995; Leavesley and others, 2005) is a modular, deterministic, distributed-parameter, physical-process-based model developed to evaluate the hydrologic response to various combinations of climate, land use, topography, and hydrogeology. It is capable of simulating the temporal and spatial distribution and routing of water in the model domain, which comprises single or multiple subbasins of any size and spatial discretization. The phrase “hydrologic response” refers to simulated water flow to and from the atmosphere, canopy, land surface, shallow subsurface, deep aquifers, stream segments, and lakes. A response to normal and extreme precipitation and snowmelt is simulated by basin and is a function of the temporal and spatial variability of hydrologic parameters, water sources and sinks, and storage in a subbasin. Simulated results include a water budget and values for snow dynamics, evapotranspiration, infiltration, streamflow, overland flow, soil-moisture relations, and vertical (recharge), lateral (interflow), and subsurface flows.

Simulation processes are based on physical laws, empirical relations, and associated parameters and attributes of the modeled area. Because these parameters vary spatially and temporally, each subbasin is partitioned into a series of HRUs. Each HRU represents a single, lumped area that is assumed to be homogeneous (with respect to hydrology, physical characteristics, and response) and responds instantaneously and uniformly, when precipitation and snowmelt are added to the HRU. A comprehensive description of PRMS is found in the GSFLOW documentation and software descriptions (Markstrom and others, 2008).

Digital Elevation Model

A digital elevation model (DEM) was generated by using the 30-meter grid USGS National Elevation Dataset (NED) (U.S. Geological Survey, 2007), resampled with a 10-meter grid, and processed in accordance with methods described by Viger and Leavesley (2007). Elevations were combined with the USGS National Hydrography Dataset (NHD) (U.S. Geological Survey, 2011) to incorporate known stream locations into the DEM prior to establishing the modeled area.

Modeled Area

The modeled area was based on the DEM developed for the study basin, including Spring Creek and Nittany Creek Basins, which drain north through water gaps in Bald Eagle Mountain, and the headwaters of Spruce Creek, which is drained by Halfmoon Creek and Beaver Branch (fig. 2). Spruce Creek was included in the domain so that the groundwater divide (fig. 1) near the headwaters of Spring Creek and Spruce Creek could be simulated dynamically as hydrologic conditions varied temporally. The Nittany Creek Basin was included to allow an exchange of groundwater between Spring Creek and Nittany Creek Basins.

Stream Network and Hydrologic Response Unit Delineation

The stream network and HRU delineation was simplified by using a geographic information system (GIS) database. Spatial variations in basin characteristics were determined by using the database and standard spatial processing techniques similar to those described by Battaglin and others (1993), Jeton (2000), and Jeton and others (1996). Coordinates in the database were assumed to refer to a Cartesian coordinate system with Universal Transverse Mercator (UTM), zone 18, Northern Hemisphere, with North American Datum (NAD) 1983 as the horizontal control datum.

A stream network was generated by using the DEM to create stream segments based on contributing area. The intersection of stream segments and MODFLOW-NWT cells were used in conjunction with the streamflow-routing package (SFR2) in MODFLOW-NWT to create the routing network used in GSFLOW. Surface runoff and interflow were added to stream reaches by connecting HRUs to stream segments. Each stream segment was associated with an HRU representing the riparian area approximated by a 656-foot (200-meter) distance on each side of the segment. The riparian areas (or stream buffers) were needed to optimize the surface-water and groundwater interaction along the stream network and to assure that groundwater discharge in riparian areas was not routed to upslope HRUs.

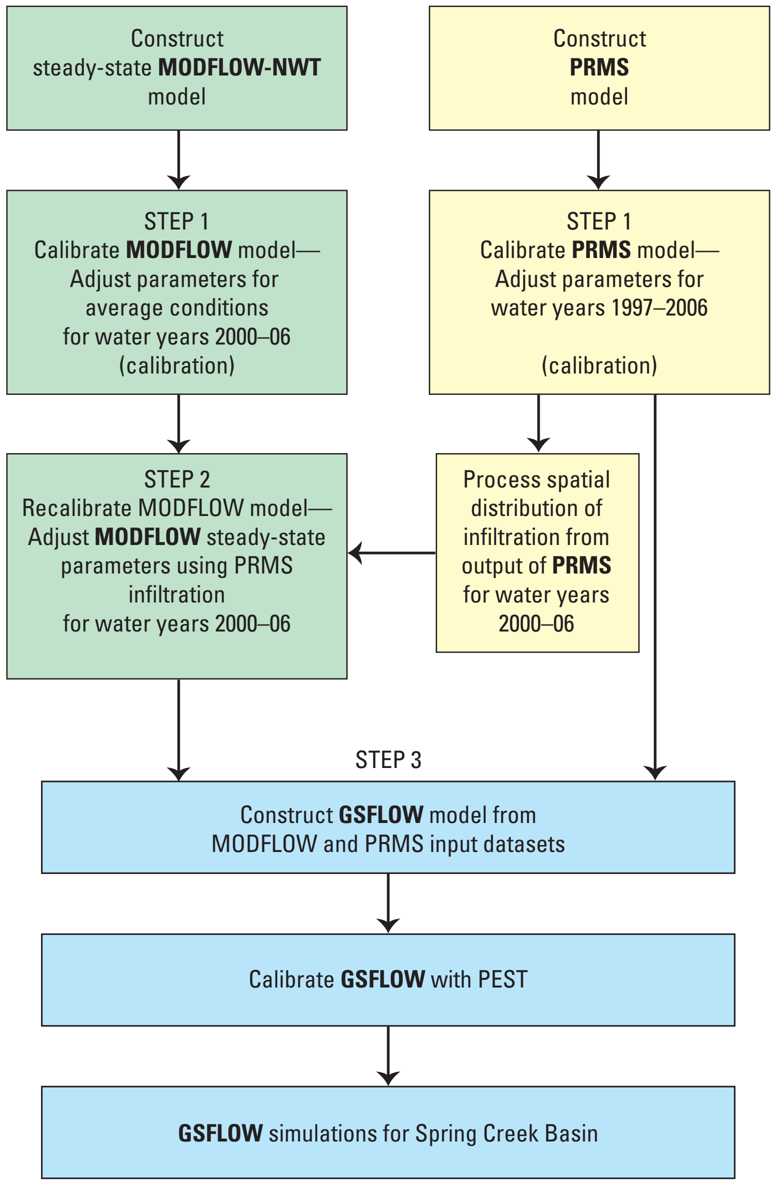


Figure 3. The strategy for development of the GSFLOW model for Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania.

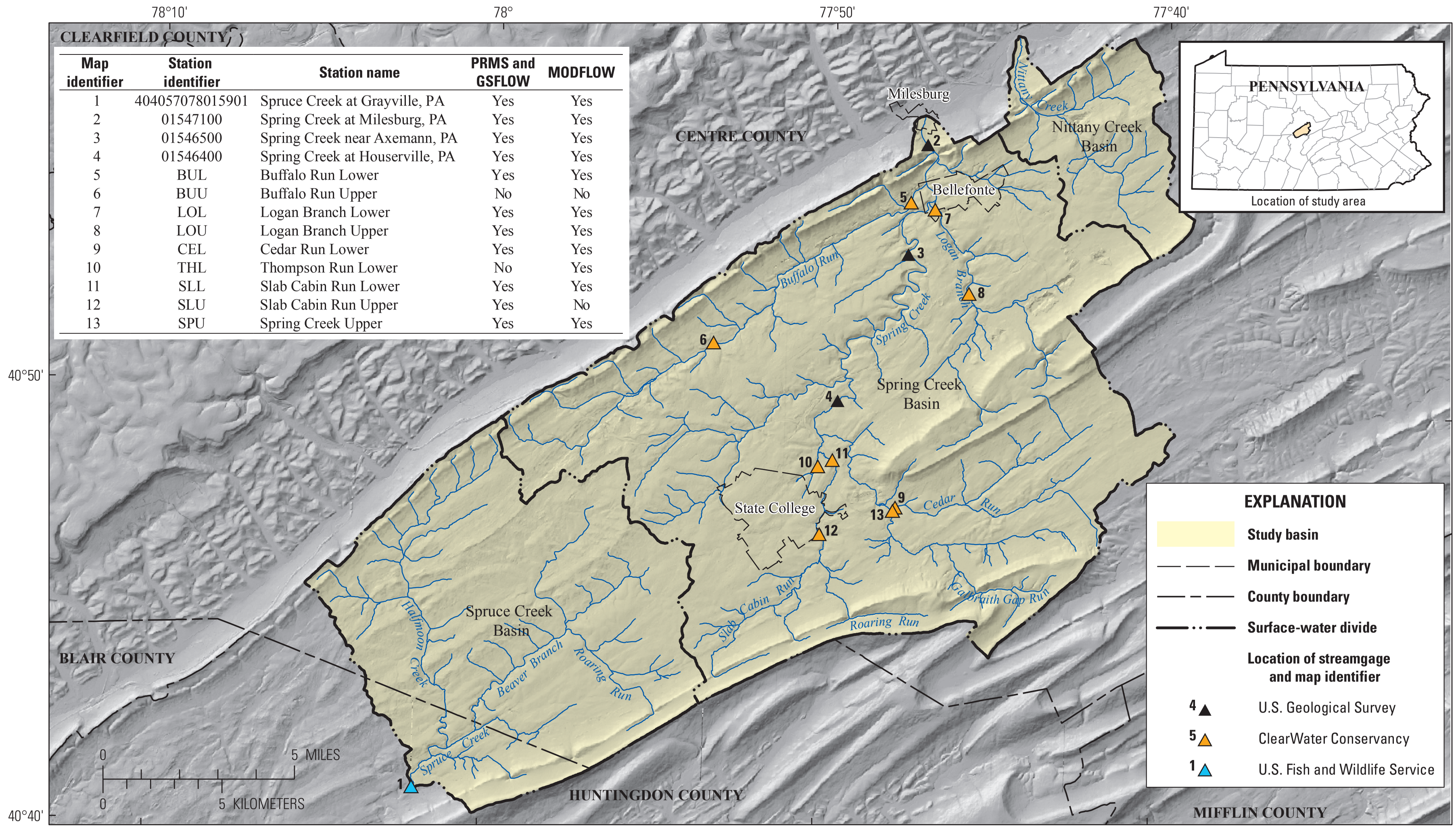
Flow direction and flow accumulation were computed for the outlet of each HRU from the DEM and used to compute contributing areas. The headwater point of each stream segment was established on the basis of a contributing-area threshold of approximately 15 mi^2; however, additional headwater streams were added manually at locations of particular interest, such as locations where streams flow into the Spring Creek Basin that do not meet the contributing-area threshold. The stream network (fig. 4) consisted of stream segments with an upper boundary as a headwater point, confluence point, or USGS or CWC streamgage and a lower boundary as a confluence point, USGS or CWC streamgage, or subbasin outlet. The stream network was used to define the left- and right-bank contributing areas and delineate initial HRUs associated with each stream segment. The initial HRU delineations were refined on the basis of soil type, geology (fig. 5), elevation, stream buffers, toe-slope boundaries, and the active MODFLOW boundary. The resulting HRUs were parameterized on the basis of areally weighted averages of subbasin characteristics—soil type, land cover, land use, and geology (Markstrom and others, 2008). GIS processing was used to remove small HRUs by merging them into adjacent, hydrologically similar HRUs (fig. 6). The Spring Creek model is composed of 14 subbasins, 829 HRUs, and 387 stream segments. The 14 subbasins are shown in figure 2.

Hydrologic Response Unit Cascades

The HRU map was analyzed to determine the cascading-flow paths for routing flow. There are multiple paths. Some HRUs cascade to one or more adjacent HRUs (upslope and downslope), some cascade to a stream segment, some terminate in swale HRUs, and some cascade to multiple stream segments. Swale HRUs were used to simulate sink holes and closed depressions on the land surface. Routines were selected to determine parameters that describe the cascade (routing surface runoff and interflow from upslope HRUs to downslope HRUs) connectivity of HRUs with the stream network. The cascade flow network was determined topologically by using GIS processing of the DEM. HRUs were grouped to define each subbasin as the contributing area to the terminus of any stream segment of interest, such as at a streamgage. Each HRU is included in a single subbasin; thus, HRUs included in a subbasin upstream from another subbasin are treated as a contributing subbasin to a downstream subbasin. HRU-to-HRU and HRU-to-stream segment cascade assignments are described in Markstrom and others (2008, p. 33–34). Flow between HRUs (cascades) that is not directly connected to a stream segment is based on topological parameters for routing surface runoff and interflow from upslope HRUs to downslope HRUs and stream segments. For PRMS-only simulations, groundwater was routed by using a similar cascading flow network. Groundwater PRMS cascades differ from HRU cascades in that groundwater reservoirs (GWR) cannot be swales. GWR cascades were the initial cascade flow paths, whereas the HRU cascade network was modified to account for swales.

Hydrologic Response Unit Parameterization

Initial HRU parameterization, including flow coefficients (gwflow_coef, slowcoef_lin, ssflow_coeff, ssr2gw_exp, ssr2gw_rate), was based on the physical characteristics of the subbasins and PRMS model defaults. Geospatial datasets related to elevation, slope, sinks, HRU area, hydraulic conductivity, aspect, vegetation type, soil type, land use, hydrology, aspect, and precipitation distribution were processed, and PRMS parameters were assigned to each HRU. Data in raster format (a gridded data structure made of rows and columns) and vector format (discrete coordinates that can be used as points or connected to create lines and polygons) were compiled to produce a database of input geospatial datasets. Sources of geospatial data include the USGS NED for elevation (U.S. Geological Survey, 2007) where slope and aspect calculations were derived by using GIS software ArcGIS version 9.2; state geology data from Pennsylvania (Pennsylvania Department of Conservation and Natural Resources, 2001); land-cover and impervious-surface data from the 2001 National Land Cover Database (Multi-Resolution Land Characteristics Consortium, 2001); and soils data (fig. 7), which were originally from the Soil Survey Geographic (SSURGO) database (Natural Resources Conservation Service, 2006) and were further processed with value-added soil characteristics (Miller and White, 1998). Selected reclassification tables (Viger and Leavesley, 2007) were used with land-cover data (fig. 8) to assist in refining the HRU characteristics. The sources of values used for selected distributed PRMS model parameters are listed in table 1 (at end of report), along with ranges of values used.



Map identifier	Station identifier	Station name	PRMS and GSFLOW	MODFLOW
1	404057078015901	Spruce Creek at Grayville, PA	Yes	Yes
2	01547100	Spring Creek at Milesburg, PA	Yes	Yes
3	01546500	Spring Creek near Axemann, PA	Yes	Yes
4	01546400	Spring Creek at Houserville, PA	Yes	Yes
5	BUL	Buffalo Run Lower	Yes	Yes
6	BUU	Buffalo Run Upper	No	No
7	LOL	Logan Branch Lower	Yes	Yes
8	LOU	Logan Branch Upper	Yes	Yes
9	CEL	Cedar Run Lower	Yes	Yes
10	THL	Thompson Run Lower	No	Yes
11	SLL	Slab Cabin Run Lower	Yes	Yes
12	SLU	Slab Cabin Run Upper	Yes	No
13	SPU	Spring Creek Upper	Yes	Yes

Base from U.S. Geological Survey digital data, 1972
Universal Transverse Mercator projection, Zone 18, NAD 1983
Streams from U.S. Geological Survey, National Hydrography Dataset, 2009
Shaded relief from PAMAP Program, 2008

Figure 4. Stream network and locations of streamgages used to derive streamflow and base-flow observations for calibrating the MODFLOW-NWT, PRMS, and GSFLOW models in Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania.

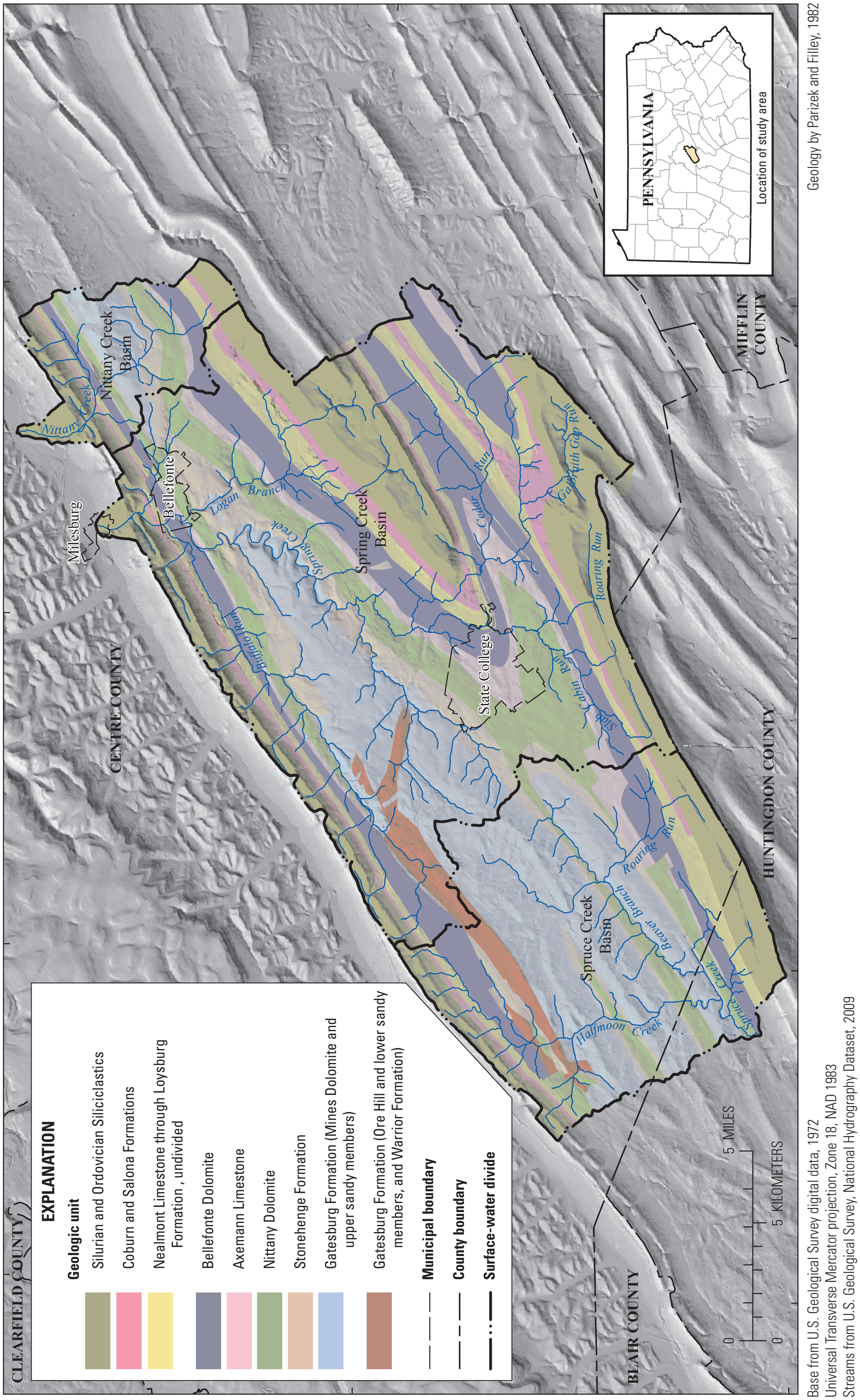
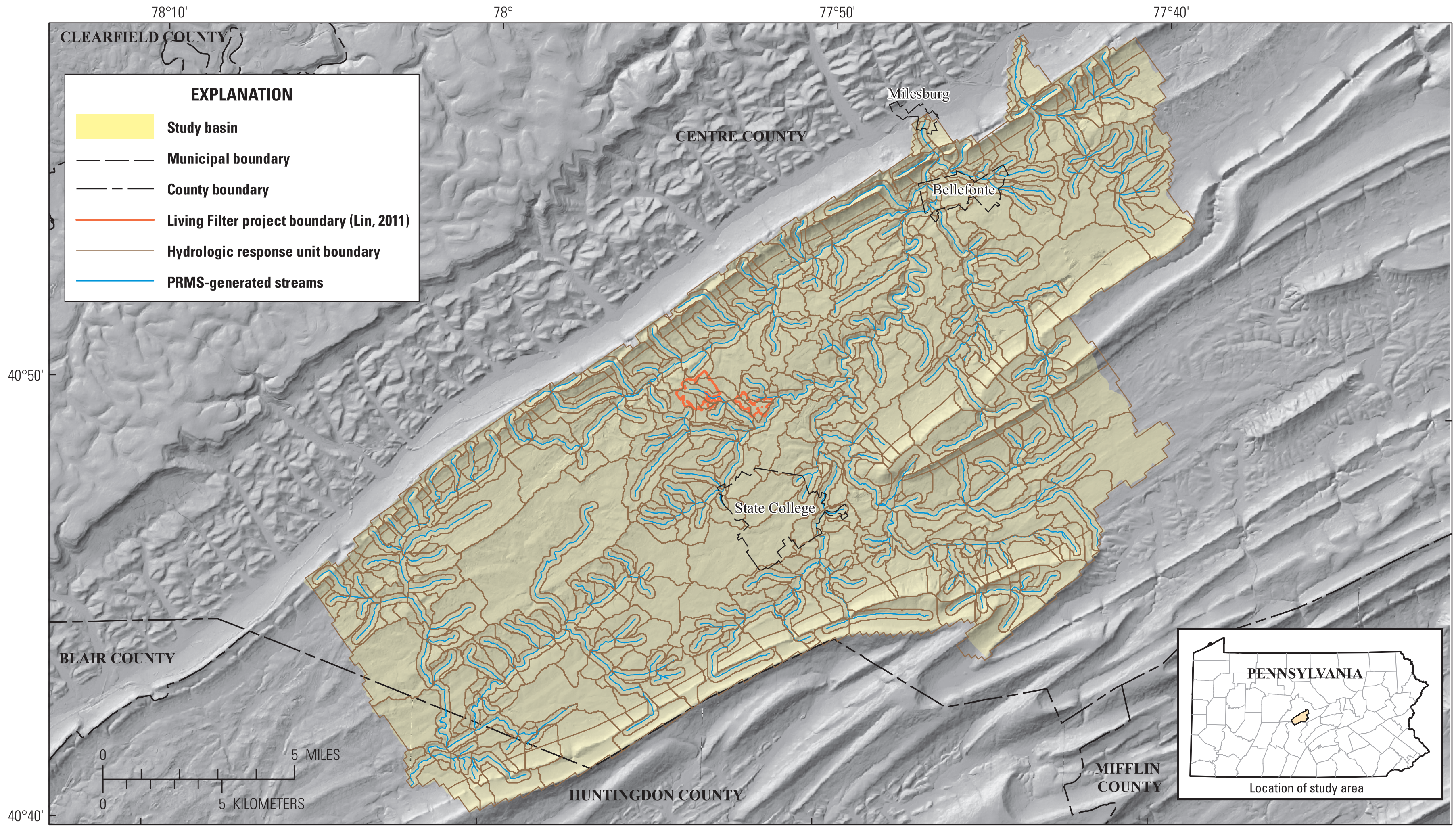
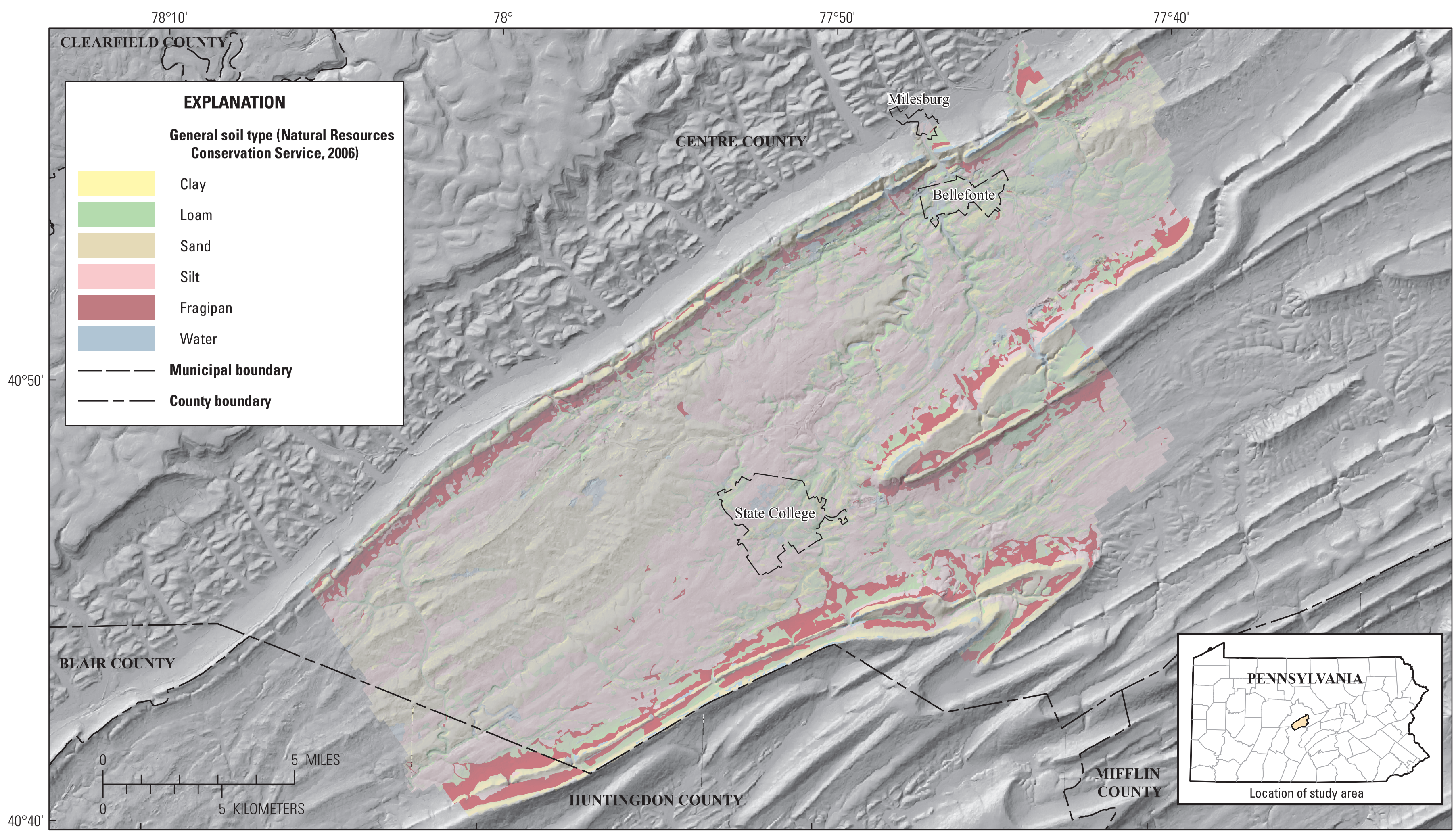


Figure 5. Bedrock geologic units of Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania.



Base from U.S. Geological Survey digital data, 1972
Universal Transverse Mercator projection, Zone 18, NAD 1983
Shaded relief from PAMAP Program, 2008

Figure 6. Location of 829 hydrologic response units in Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania.



Base from U.S. Geological Survey digital data, 1972
Universal Transverse Mercator projection, Zone 18, NAD 1983
Shaded relief from PAMAP Program, 2008

Figure 7. General soil types in Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania.

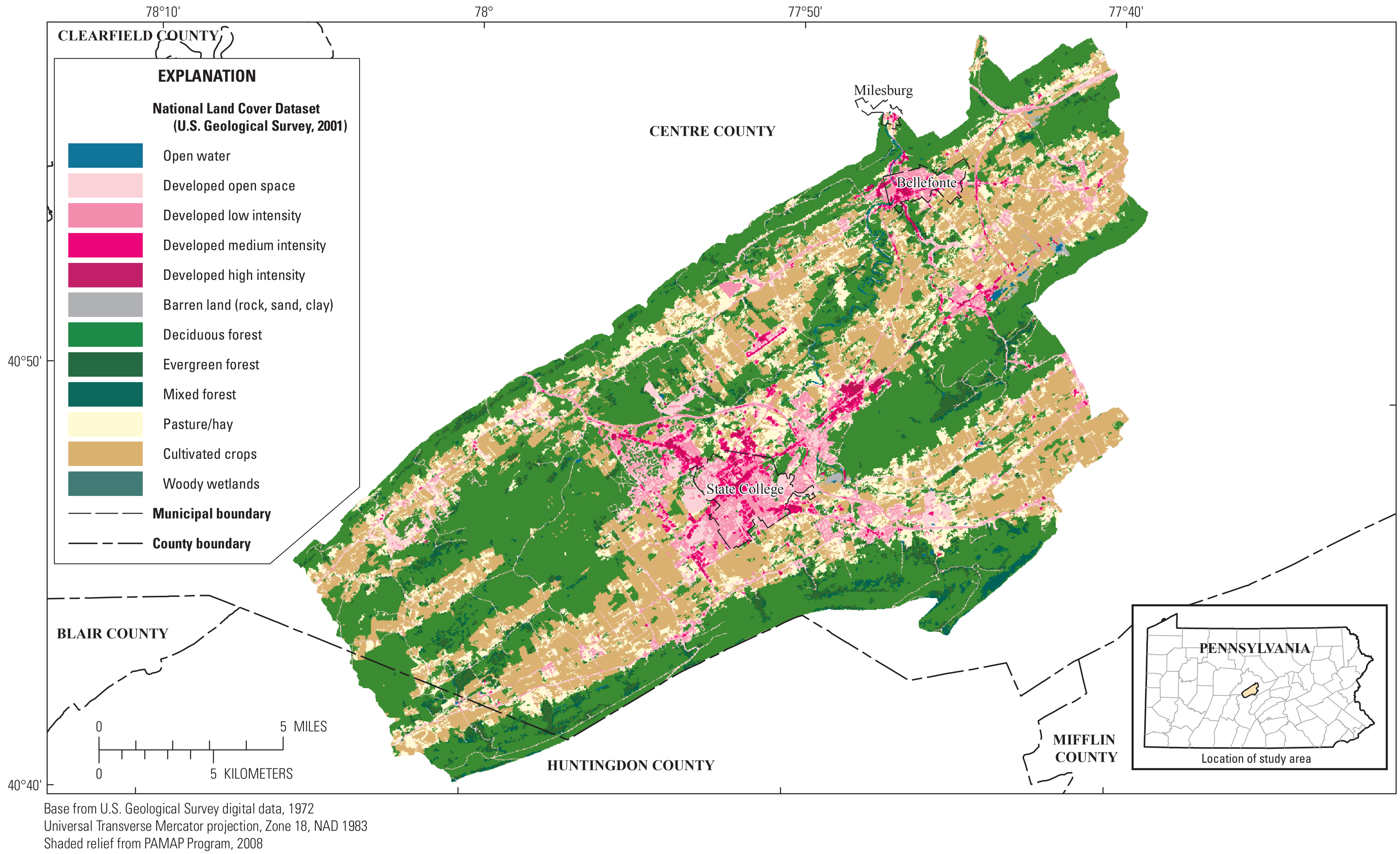


Figure 8. Land cover in Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania.

Climate Data

The forcing functions for PRMS are based on climate time-series data and include (1) precipitation, (2) maximum and minimum air temperatures, (3) potential evapotranspiration, and (4) solar radiation. Because GSFLOW operates in a daily mode only, the time-series data were organized by using daily time steps and provided as input to GSFLOW in climate-by-HRU (CBH) files, which have the same format as PRMS data files (Markstrom and others, 2008, p. 139–140). Five CBH files were input, one for each climate-forcing type: daily precipitation, maximum air temperature, minimum air temperature, potential evapotranspiration, and actual solar radiation. The CBH files provided a value for each HRU for each day.

Precipitation data for meteorological stations were obtained from multiple sources, including 13 meteorological stations (table 2) in and near the modeled area. Data were acquired by using the Downsizer, a computer application that locates and downloads time-series data from environmental databases that are used to parameterize models such as PRMS (Ward-Garrison and others, 2009) and were augmented with data from the Pennsylvania State Climatologist office. The meteorological data were preprocessed by using an IDE weighting algorithm to generate the precipitation, minimum air temperature, and maximum air temperature CBH files for the simulation period. The IDE method distributes precipitation and maximum and minimum temperatures to each HRU using the closest climate-station elevations above and below a given HRU's elevation and linearly interpolates climate values for the HRU on the basis of the data from these two stations.

Wastewater effluent to the canopy has been included in the model from the Living Filter (Pennsylvania State University, 2012), which is a water re-use project that began in 1963 (figs. 1 and 2). Approximately 2.7 million gallons per day (Mgal/d) of wastewater from the Pennsylvania State University (PSU) is applied to approximately 600 acres of forests, croplands, and fields as tertiary treatment (Richardson, 2011). In addition to distributed precipitation (38.4 inches on average), approximately 62.4 inches of water per year (in/yr) related to reuse was added in GSFLOW to the application area to simulate the operation of the Living Filter.

Potential evapotranspiration was simulated by PRMS using a modified Jensen-Haise formulation (Markstrom and others, 2008, p. 43). Solar radiation was estimated by using computed daily clear-sky short-wave solar radiation for each HRU (Markstrom and others, 2008, p. 41–42). Modification of a degree-day method was used to compute actual solar radiation for each HRU (Markstrom and others, 2008, p. 42).

Table 2. Meteorological stations used to generate the climate data for the Precipitation-Runoff Modeling System-only simulations for Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania.

[NAVD 88, North American Vertical Datum of 1988]

Station number	Station name	Latitude	Longitude	Elevation, in feet above above NAVD 88
361480	Clarence	41.049	-77.941	1,390
360482	Beavertown 1 NE	40.774	-77.157	540
360132	Altoona	40.523	-78.369	1,280
369022	Tyrone	40.664	-78.219	890
369714	Williamsburg	40.467	-78.200	845
365109	Lock Haven Sewage Plant	41.117	-77.450	566
364159	Huntingdon	40.515	-78.003	685
367409	Renovo	41.330	-77.738	660
368449	State College	40.793	-77.867	1,170
364992	Lewistown	40.587	-77.570	460
364853	Laurelton Center	40.902	-77.214	800
366921	Philipsburg 2 S	40.872	-78.215	1,720
365790	Millheim	40.884	-77.474	1,120

PRMS-Only Model Calibration and Results

Initial values of most PRMS parameters were computed by using methods documented by Viger and Leavesley (2007), Battaglin and others (1993), Jeton (2000), and Koczot and others (2005). Other parameters were estimated on the basis of GIS analysis, PRMS default values, and other datasets available for the modeled area. Initial parameter values were modified during the model calibration procedure by using manual and automated methods to minimize the difference between simulated and measured (or independently computed) potential evapotranspiration, solar radiation, and streamflow. Streamflow was recorded at USGS and CWC streamgages (fig. 4). Manual calibration methods were based on previous PRMS calibration experience and are summarized in table 3.

The water budget components for the PRMS-only simulation were computed for water years 2000–06. To generate budgets for those years, the PRMS simulation period was initialized three years prior to WY 2000, which provided time for the simulated hydraulic system to adjust from the initial conditions that were assigned to the model. The major water budget components are summarized by water year in table 4. During water years 2000–06, 2001 was the driest year and 2004 the wettest year on the basis of both simulated precipitation and runoff amounts.

The simulated mean infiltration rate for water years 2000–06 from PRMS was 14.7 inches per year (in/yr) for the basin as a whole. PRMS-derived infiltration (vertical flows from the PRMS soilzone) is a downward vertical flux that originates at the land surface. This process differs from gravity drainage (potential recharge from the PRMS soilzone by HRU) and recharge from the UZF Package to MODFLOW generated by GSFLOW, which is a vertical flux from the unsaturated zone to the saturated zone for each model cell.

Simulated mean infiltration rates ranged throughout the basin from approximately 2.1 to 72.9 in/yr (fig. 9). The greatest amount of infiltration was simulated in the carbonate-bedrock valley near the Living Filter, along Logan Branch, along the toe slopes of Nittany and Tussey Mountains, along the Gatesburg Ridge near the Scotia Barrens, along Buffalo Run and Spruce Creek, and in Penns Valley. The variation is attributed to the distribution of precipitation, variable slopes, and the runoff characteristics of land-use types in the study basin.

MODFLOW-Only Model Development

The finite-difference computer code MODFLOW-NWT (Niswonger and others, 2011) was used to simulate three-dimensional (3D), steady-state, groundwater flow of the study basin. The MODFLOW-NWT model was constructed in units of meters and days. The length unit of meters was converted into feet for this report, resulting in some values that may seem unusual or may convey more precision than is warranted. MODFLOW-NWT is a code based on MODFLOW-2005 (Harbaugh, 2005) and includes a Newton solver that can be used to solve the groundwater-flow equation for situations where the fluctuating water table causes drying and rewetting of model cells (Hunt and Feinstein, 2012). A graphical user interface linked to Argus Numerical Environments was used for pre- and post-processing of data (Winston, 2000).

Spatial and Temporal Discretization

The study area was divided into a finite-difference grid (fig. 10) with three layers, 104 rows, and 216 columns. The horizontal dimensions of the cells were uniform 656 by 656 feet (200 by 200 meters) in horizontal dimension. The model grid was constructed with rows oriented N. 55° E. to align with the general strike of geologic units in the area. The active model area coincides with the HRU boundary. The orientation of model rows along the strike of dipping units is important because fractures and solution openings that enhance permeability are better developed parallel to strike, and shaley beds tend to impede the movement of water across the strike of beds (Parizek and others, 1971, p. 40).

The steady-state MODFLOW-NWT model was based on water years 2000–06 and was assumed to represent the average groundwater conditions during that period. Recharge for initial simulations was assumed to be spatially uniform (calibration step 1, fig. 3), then was refined to use the average infiltration at each PRMS HRU for water years 2000–06 to represent a spatially varied recharge distribution (calibration step 2, fig. 3). Changes caused by seasonal variations in recharge or pumping were not simulated in the steady-state model but were incorporated in GSFLOW. For water years 2000–06, groundwater withdrawals, surface-water withdrawals, and discharges to surface water were varied by stress period on a monthly basis in GSFLOW.

Boundary Conditions

The elevation of the top of each cell in the uppermost model layer (layer 1) was set equal to the elevation of land surface determined as the mean of all data points from the USGS 30-meter DEM falling within the cell. The land-surface elevations assigned to model cells ranged from 680 to 2,399 feet, and the maximum elevation difference between adjacent cells was about 200 ft. The thickness of each model layer was set to a uniform value of 300 feet, so the total model thickness was 900 feet throughout the study area.

For this study, groundwater movement is assumed to be minimal below the base of the model (900 ft below land surface). The depth of active flow is not well known, but in Centre County, most high yielding zones in wells are generally encountered within weathered bedrock at depths of less than 400 ft below land surface, and evidence of secondary permeability in limestone mines was almost entirely absent at depths greater than about 500 ft (Wood, 1980, p. 31–32). Important water-bearing zones have been reported as deep as 600 ft in production wells drilled in the Gatesburg Formation, and Parizek and others (1971, p. 61) hypothesized that groundwater flows at depths greater than 1,000 feet below land surface within the Dale Sandstone Member of the

Table 3. Description of manual calibration parameters with ranges for Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania, water years 2000–06.

[PRMS, Precipitation-Runoff Modeling System; Min, minimum; Max, maximum; NRMSE, normalized root mean square error; HRU, hydrologic response unit; GWR, groundwater reservoir]

PRMS calibration data set	Objective function NRMSE	PRMS parameters used to calibrate model state	Range Min	Range Max	Parameter description	Comments
Water budget	Monthly mean Mean monthly Annual mean	rain_adjust (nhru, nmonths)	0.6	1.4	Precipitation adjust factor for rain days (unitless)	Calibrate the mean.
		snow_adjust (nhru, nmonths)	0.6	1.4	Precipitation adjust factor for snow days (unitless)	
Daily flow timing (all flows)	Daily mean Monthly mean	adjmix_rain (nmonths)	0.6	1.4	Factor to adjust rain proportion in mixed rain/snow event (unitless)	Calibrate mean for spatial parameters. Weight the daily mean more than the monthly mean.
		slowcoeff_lin (nhru)	0.001	0.5	Linear coefficient in equation to route gravity-reservoir storage down slope for each HRU (1/day)	
		soil_moist_max (nhru)	2	10	Maximum available water holding capacity of soil profile (inches)	
		soil_rechr_max (nhru)	1.5	5	Maximum available water holding capacity for soil recharge zone (inches)	
Daily flow timing (all flows)	Daily mean Monthly mean	fastcoef_lin (nhru)	0.001	0.8	Coefficient to route preferential-flow storage down slope (1/day)	Calibrate mean for spatial parameters. Weight the daily mean more than the monthly mean. Subdivide high flow.
		sat_threshold (nhru)	1	15	Water holding capacity of the gravity and preferential flow reservoirs; 2x soil_moist_max initial value (inches)	
		smidx_coef (nhru)	0.001	0.05	Coefficient in non-linear surface runoff contributing area algorithm (1/day)	
Daily flow timing (all flows)	Daily mean Monthly mean	gwflow_coef (ngw)	0.001	0.5	Linear coefficient to compute groundwater discharge from each GWR (1/day)	Calibrate the mean for spatial parameters. Data subdivide: low flows
		soil2gw_max (nhru)	0	0.5	Maximum amount of capillary reservoir excess routed directly to the GWR (inches)	
		ssr2gw_rate (nssr)	0.05	0.8	Linear coefficient used to route water from the gravity reservoir to the GWR (1/day)	

Table 4. Water budget components from the Precipitation-Runoff Modeling System-only simulation to generate the steady-state infiltration distribution for Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania, water years 2000–06.

[in, inches; surface water and energy budgets simulated by using Precipitation-Runoff Modeling System (PRMS), Version 3.4050 2011-12-12; start time: 1996/10/01 00:00:00; end time: 2006/09/30 00:00:00; sum of hydrologic response unit (HRU) areas: 228.7 square miles (mi^2); active basin area: 228.7 mi^2; impervious basin area: 0.3 mi^2; pervious basin area: 228.4 mi^2]

Water year	Precipitation (in)	Evapotranspiration (in)	Storage (in)	Simulated runoff (in)	Measured runoff (in)
2000	35.008	26.786	1.314	10.782	10.935
2001	30.946	22.412	2.779	7.056	9.511
2002	39.666	28.228	4.139	10.057	10.437
2003	55.849	31.678	6.446	21.822	15.138
2004	58.629	34.406	6.434	24.191	20.548
2005	34.732	21.813	1.265	18.058	16.571
2006	44.189	27.586	3.338	14.502	11.891

Bellefonte Dolomite. However, for the purpose of simulating basin-wide surface-water and groundwater budgets, accounting for groundwater down to 900 ft below land surface is probably sufficient.

Lateral Boundaries

The lateral extent of the modeled area was defined with no-flow, general-head, and specified-head boundaries (fig. 10). No-flow (inactive) cells were placed around the perimeter of the modeled area except (1) along the topographic divide separating Halfmoon Creek (within the Spruce Creek Basin) from Warriors Mark Run (outside of the modeled area), which was simulated by the use of a general-head boundary, and (2) along the divide separating Cedar Run (within the Spring Creek Basin) from Penns Creek Basin (outside of the modeled area), which was simulated by the use of specified heads (fig. 10).

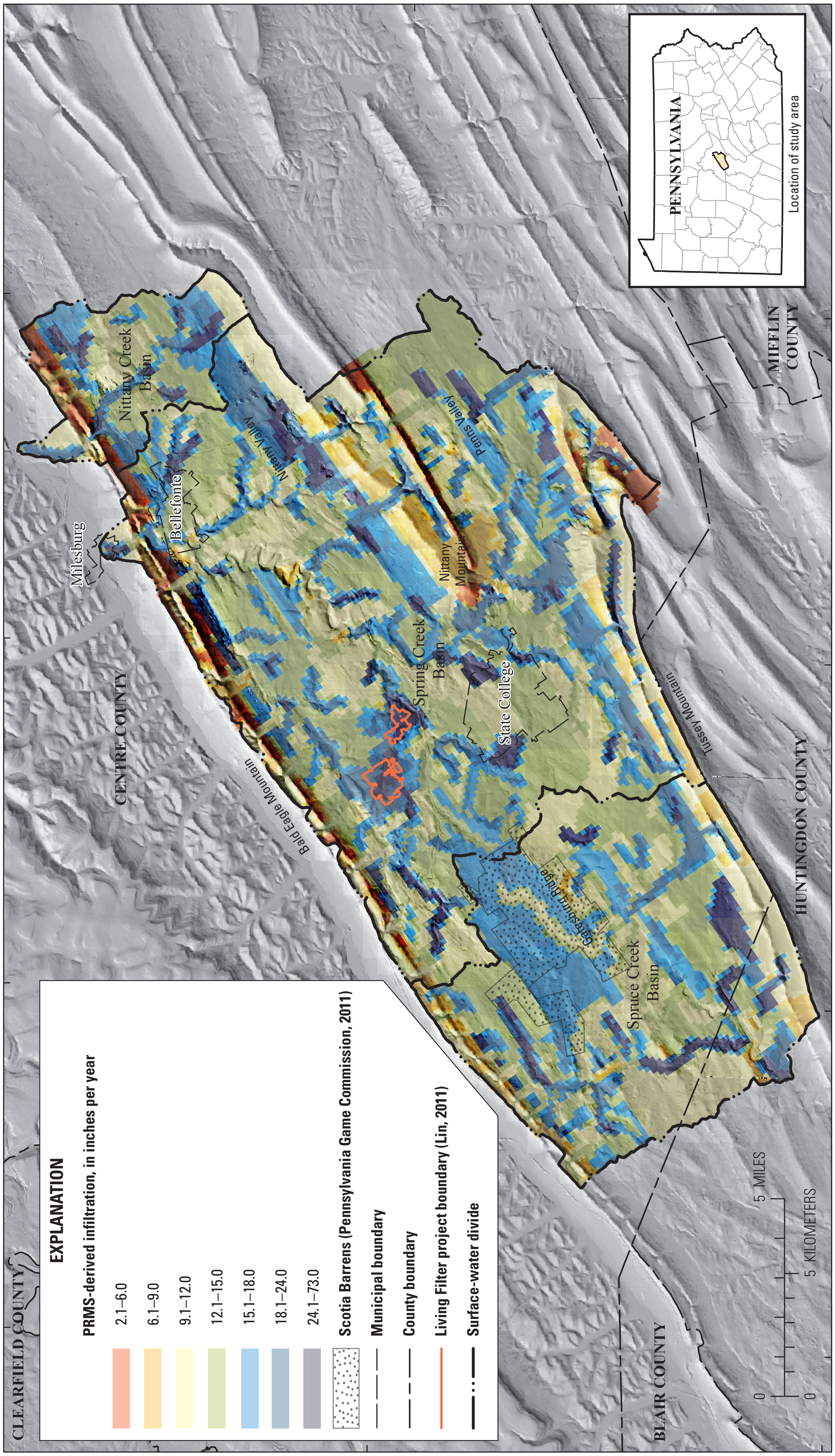
No-flow cells prohibit transfer of water across Bald Eagle Mountain to the northwest and Tussey Mountain to the southeast. No-flow cells also follow topographic divides separating parts of study basin from Penns Creek, Little Fishing Creek, and Lick Run Basins to the east and northeast.

General-head cells allow a transfer of groundwater across the topographic divide between Halfmoon Creek and Warriors Mark Run Basins. The general-head boundary allows groundwater within the carbonate rocks to cross the divide and move out of the modeled area to discharge to Warriors Mark Run, owing to its lower elevation and the high permeability of the carbonate rocks. The magnitude of the flow is related to the difference between the elevation of the groundwater levels simulated by the model at the general-head boundary and the reference elevations assigned to Warriors Mark Run, and to the hydraulic conductance between those locations. Reference elevations were determined by temporarily extending the model grid to Warriors Mark Run, simulating groundwater flow paths from the divide to the creek, and assigning reference values to the divide equal to the elevation of the flow path terminus where groundwater discharged to Warriors Mark Run.

Specified-head cells separating parts of the Cedar Run and Penns Creek watersheds also allow the transfer of water across the divide in the carbonate-rock units. The direction and magnitude of flow depend upon the difference between the groundwater levels specified at the boundary and adjacent cells. Groundwater levels along the boundary of the Spring Creek model were set to the elevation of the water table mapped by Taylor (1997).

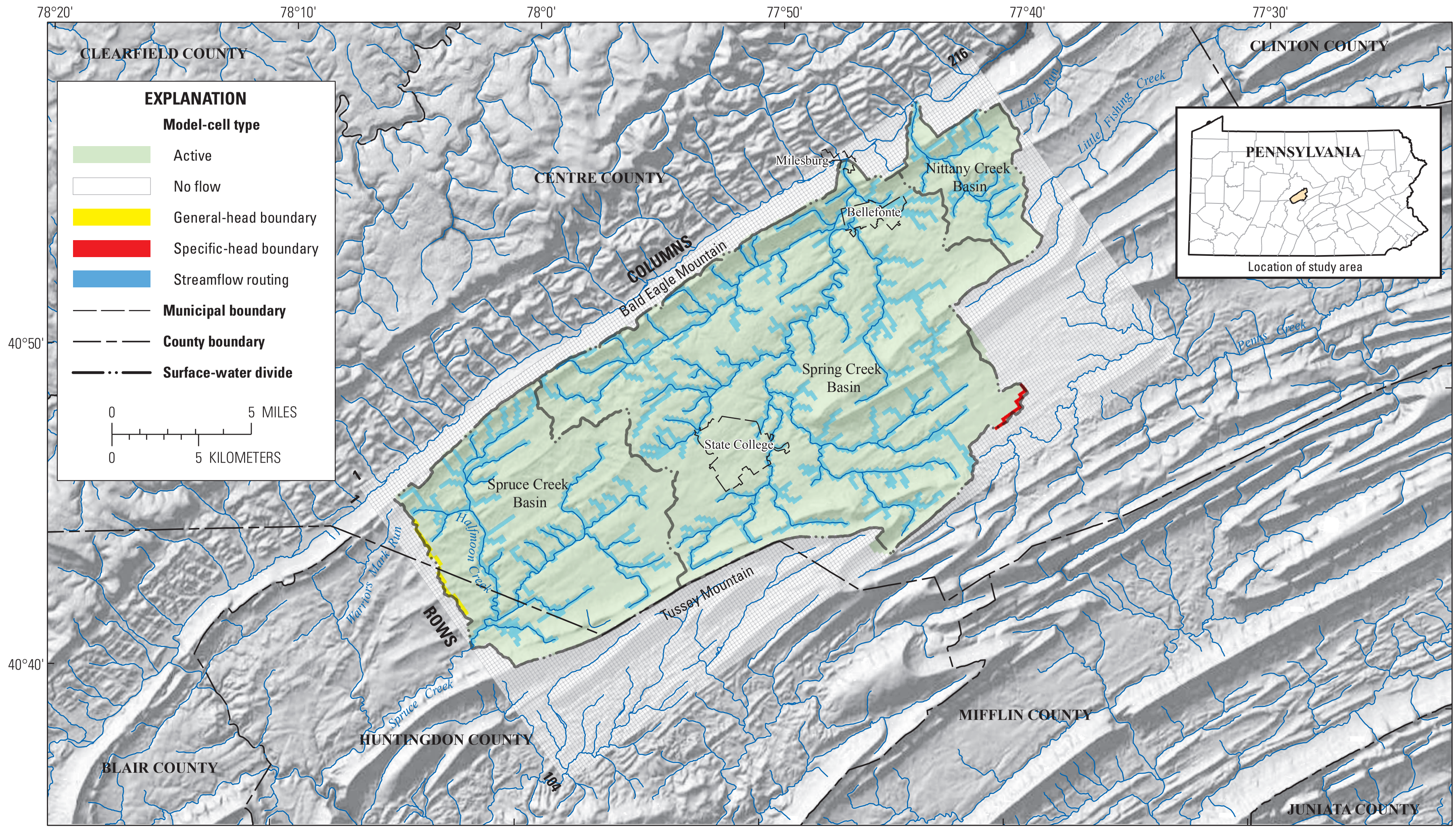
Infiltration from Precipitation

Groundwater recharge (water reaching the water table) is customarily assigned in the recharge (RCH) package of MODFLOW-NWT. In this study, however, the PRMS routine in GSFLOW computes infiltration through the root zone from each HRU, passing that flux to the UZF package of MODFLOW-NWT. Recharge to the water table is computed in the UZF package, so the RCH package is not needed. Thus, the MODFLOW-NWT model was constructed by assigning the spatially variable distribution of average infiltration to the UZF package that was derived from PRMS simulations for water years 2000–06. The infiltration rate from PRMS, simulated as the sum of PRMS vertical fluxes from the soil zone from each HRU (fig. 9), is assigned as infiltration to



Base from U.S. Geological Survey digital data, 1972
Universal Transverse Mercator projection, Zone 18, NAD 1983
Shaded relief from PAMAP Program, 2008

Figure 9. Mean infiltration rate simulated by PRMS for Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania, water years 2000–06.



Base from U.S. Geological Survey digital data, 1972
Universal Transverse Mercator projection, Zone 18, NAD 1983
Streams from U.S. Geological Survey, National Hydrography Dataset, 2009
Shaded relief from PAMAP Program, 2008

Figure 10. Finite-difference grid and boundaries of the MODFLOW-NWT model for Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania.

MODFLOW cells on the basis of the percentage of each HRU in the cell. The simulated rate of infiltration averaged 14.7 in/yr for the study basin and ranged from about 2.1 to 72.9 in/yr.

The average infiltration rate for the study basin of 14.7 in/yr is slightly less than the amount needed to provide the base flow computed at the USGS streamflow-gaging station 01547100 Spring Creek near Milesburg. During water years 2000–06, average base flow determined by the local minimum method of hydrograph separation (Pettyjohn and Henning, 1979) by use of the HYSEP program (Sloto and Crouse, 1996) was 196 cubic feet per second (ft^3/sec). Recharge of 15.2 in/yr is needed to provide this base flow, assuming a contributing groundwater basin of 175 mi^2.

Streams

Streamflow is simulated by using the SFR2 package (Niswonger and Prudic, 2005), which allows streams to gain or lose water and accounts for the flow in each stream cell so that losses cannot exceed the simulated streamflow. Streams were represented in model layer 1 by 387 segments made up of 3,444 reaches (fig. 10). Unsaturated flow beneath the streams was also simulated. The elevation of the top of the streambed in each SFR reach was assigned 3.28 ft (1 m) less than the nearest elevation derived from the USGS 10-meter DEM and was adjusted to insure that the streambed elevation always decreased downstream. Thickness of the streambed was set to 3.28 ft for all stream segments. Stream width was varied by segment from 3.3 to 66 ft on the basis of 39 locations where the stream width was measured in the field. Hydraulic conductivity of the streambed was assigned an initial value of 2 feet per day (ft/d) on non-carbonate rocks and 13.1 ft/d on carbonate rocks, which are based on the approximate difference in the horizontal hydraulic conductivity between the non-carbonate and carbonate rocks; hydraulic conductivity was adjusted during model calibration. Stream slope for each segment was determined as the difference between the upstream and downstream elevations divided by segment length. Unsaturated-zone properties beneath all stream reaches were set to constant values. Vertical hydraulic conductivity was set equal to the vertical hydraulic conductivity of layer 1 beneath the stream, and the saturated water content was set equal to 0.03.

Water was added at the upstream end of stream segments in the SRF2 package to simulate major wastewater discharges to streams from municipalities and industry. Water was subtracted from SFR2 segments to simulate major withdrawals from streams for water supply and other uses. Simulated discharges to streams totaled about 20.5 ft^3/sec, and withdrawals from streams totaled about 9.4 ft^3/sec (fig. 11 and table 5). Wastewater discharge from PSU is a source of recharge. It was not included in the steady-state MODFLOW-NWT simulation but was included in the GSFLOW model. The average withdrawal from Roaring Run (fig. 2) of about 330,000 gallons per day by the State College Borough Water Authority (SCBWA) was not simulated because the withdrawal is from a reservoir that was not included in the model. Without the reservoir, simulated streamflow was insufficient to supply a withdrawal of this magnitude, so the model, as constructed for this study, is not designed to accurately simulate flow in Roaring Run.

Wells

Forty-five groundwater withdrawals were simulated by the steady-state model using the multi-node well (MNW) package (Halford and Hanson, 2002). Wells were used to represent groundwater withdrawals from 5 mines and 40 production wells totaling about 14.5 Mgal/d (fig. 12 and table 6). Wells were incorporated into the model to represent the mean withdrawals during water years 2000–06 from the PSU and SCBWA production wells, along with other water purveyors with withdrawals greater than 50 gallons per minute (gal/min). The average withdrawal rate was assigned to each well for the steady-state simulation, and the MNW package computed the contribution from each model layer on the basis of the transmissivity and groundwater levels in each layer.

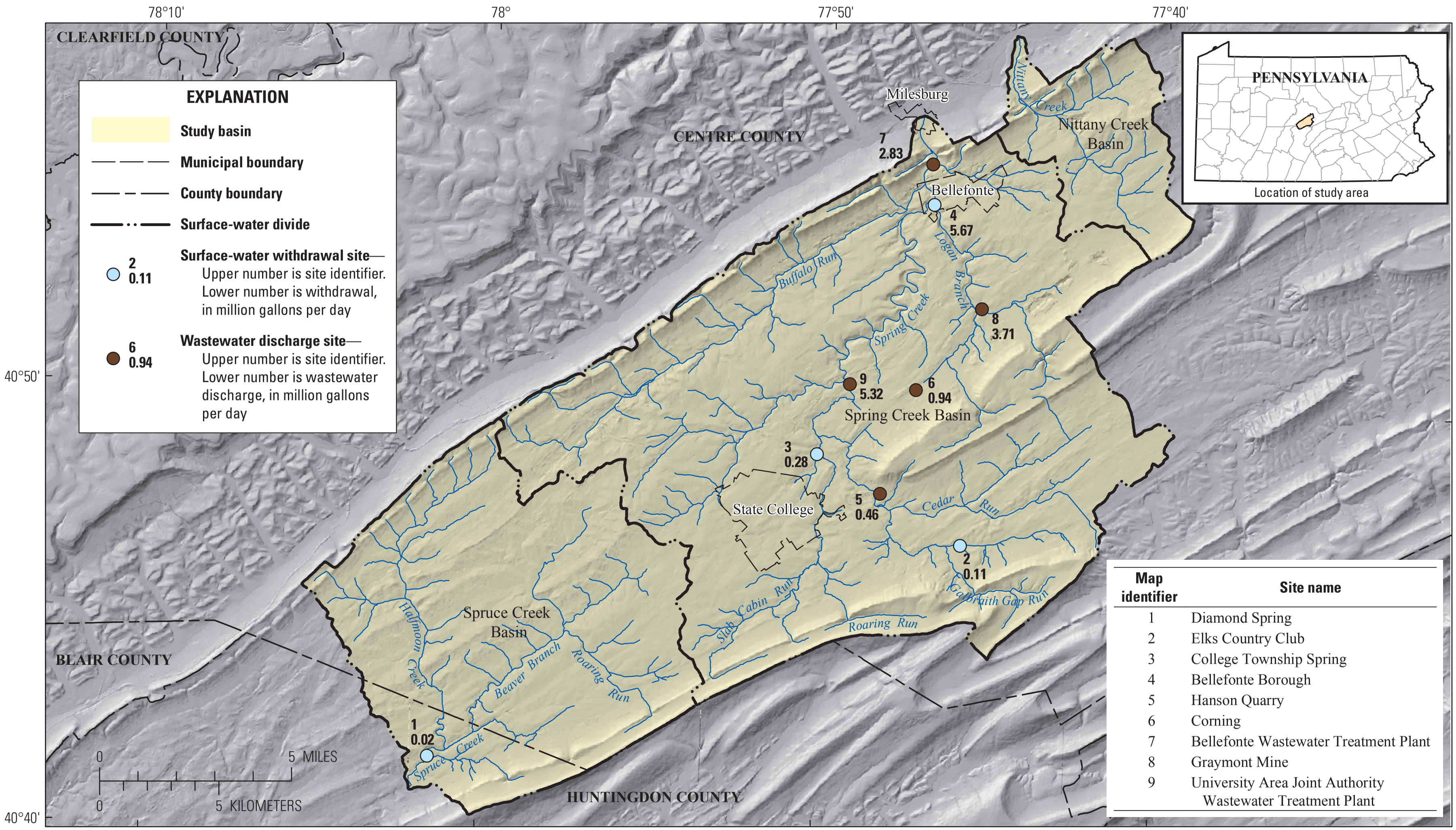
Table 5. Discharges to streams and withdrawals from streams simulated by using the Streamflow-Routing Package of MODFLOW-NWT model for Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania.

[m^3/d, cubic meters per day; Mgal/d, million gallons per day; ft^3/s, cubic feet per second; WWTP, wastewater treatment plant; UAJA, University Area Joint Authority; TWP, township]

Identifier	Rate		
	m^3/d	Mgal/d	ft^3/s
Wastewater discharges[1] to streams in model layer 1			
Hanson Quarry	1,750	0.46	0.72
Corning	3,540	0.94	1.45
Bellefonte WWTP	10,721	2.83	4.38
Graymont Mine	14,030	3.71	5.73
UAJA WWTP	20,150	5.32	8.24
Total discharge	50,191	13.26	20.51
Withdrawals[2] from streams in model layer 1			
Diamond Spring	78	0.02	0.03
Elks Country Club	414	0.11	0.17
College Twp Spring	1,075	0.28	0.44
Bellefonte Borough	21,450	5.67	8.77
Total withdrawal	23,017	6.08	9.41

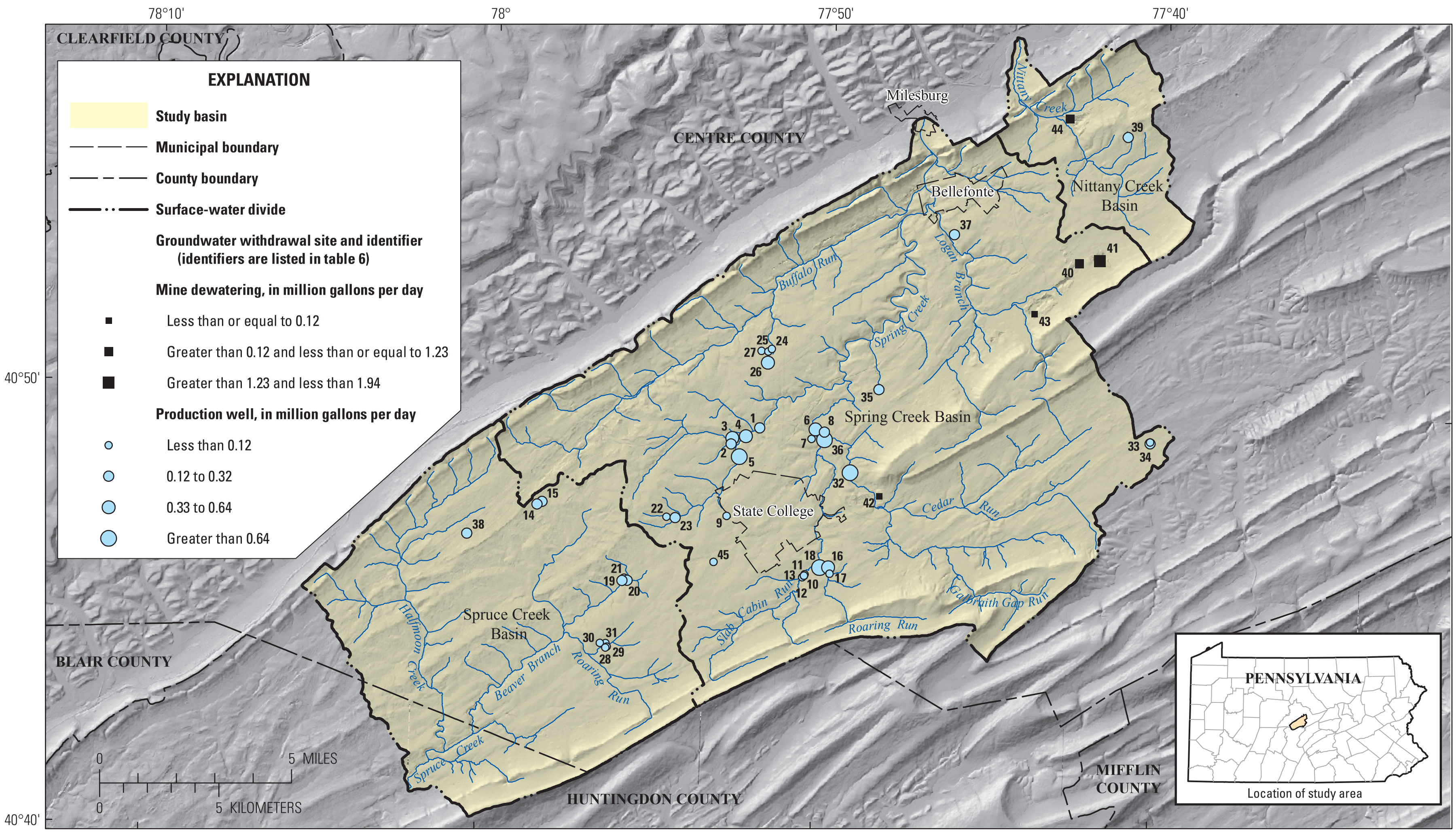
[1]Penn State University wastewater is discharged as a land application, so it is not included in the list of surface-water discharges.

[2]The average withdrawal of 330,000 gallons per day from Roaring Run is not simulated in the model.



Base from U.S. Geological Survey digital data, 1972
Universal Transverse Mercator projection, Zone 18, NAD 1983
Streams from U.S. Geological Survey, National Hydrography Dataset, 2009
Shaded relief from PAMAP Program, 2008

Figure 11. Location of surface-water withdrawals and discharges simulated by the MODFLOW-NWT model for Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania.



Base from U.S. Geological Survey digital data, 1972
Universal Transverse Mercator projection, Zone 18, NAD 1983
Streams from U.S. Geological Survey, National Hydrography Dataset, 2009
Shaded relief from PAMAP Program, 2008

Figure 12. Location of groundwater withdrawals simulated by the MODFLOW-NWT model for Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania.

Table 6. Groundwater withdrawals simulated using the MODFLOW-NWT steady-state model for Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania.

[m^3/d, cubic meters per day; Mgal/d, million gallons per day; ft^3/s, cubic feet per second]

Map identifier	Local name of well	Rate		
		m^3/d	Mgal/d	ft^3/s
	Pennsylvania State University			
1	UN14	1,211	0.320	0.50
2	UN16	664	0.175	0.27
3	UN17	1,528	0.404	0.62
4	UN24	1,662	0.439	0.68
5	UN26	3,115	0.823	1.27
6	PS33	1,485	0.392	0.61
7	PS35	181	0.048	0.07
8	PS34	902	0.238	0.37
9	PS37	13	0.003	0.01
	State College Borough Water Authority			
10	SCBWA 07	75	0.020	0.03
11	SCBWA 08	75	0.020	0.03
12	SCBWA 11	75	0.020	0.03
13	SCBWA 14	43	0.011	0.02
14	SCBWA 17	1,041	0.275	0.43
15	SCBWA 19	1,041	0.275	0.43
16	SCBWA 22	1,671	0.441	0.68
17	SCBWA 24	141	0.037	0.06
18	SCBWA 25	5,492	1.451	2.24
19	SCBWA 41	1,027	0.271	0.42
20	SCBWA 43	890	0.235	0.36
21	SCBWA 53	890	0.235	0.36
22	SCBWA 55	30	0.008	0.01
23	SCBWA 57	814	0.215	0.33
24	SCBWA 62	55	0.015	0.02
25	SCBWA 63	100	0.026	0.04
26	SCBWA 64	2,411	0.637	0.99
27	SCBWA 65	42	0.011	0.02
28	SCBWA 71	166	0.044	0.07
29	SCBWA 73	267	0.070	0.11
30	SCBWA 78	178	0.047	0.07
31	SCBWA 79	6	0.002	0.00
	Other water purveyors			
32	CE162 Lemont	3,103	0.820	1.27
33	Centre Hall Well 8	81	0.022	0.03
34	Centre Hall Well 9	815	0.215	0.33
35	College Township Rogers Silo	773	0.204	0.32
36	College Township Spring Creek Well	3,468	0.916	1.42
37	Spring Township PW1 Carles Well	852	0.225	0.35
38	Upper Halfmoon Township Well 5	542	0.143	0.22
39	Walker Township Zion 2	454	0.120	0.19
	Industrial and mineral use			
40	Gentzel Deep Mine	4,636	1.225	1.89
41	Gentzel Quarry	7,357	1.944	3.01
42	Hanson Oak Hall Quarry	288	0.076	0.12
43	Hawbaker Pleasant Gap White Rock Quarry	432	0.114	0.18
44	HRI—Curtin Gap Quarry	4,186	1.106	1.71
45	Spectrum Control RW-1	452	0.119	0.18
Total withdrawals		**54,728**	**14.458**	**22.37**

Evapotranspiration

Evapotranspiration from groundwater was simulated with the UZF package. A potential evapotranspiration rate of 25.5 in/yr was used, as computed for State College by Waltman and others (1997, p. 217) using a modified Thornthwaite approach. An extinction depth of 6.56 ft (2 meters) below land surface was assumed. When linked to the GSFLOW model, the potential evapotranspiration (PET) from MODFLOW-NWT is replaced by values for each HRU simulated by PRMS on the basis of daily climate conditions. Actual evapotranspiration is computed in GSFLOW as the sum of each component of evapotranspiration (ET) in the sequence (1) canopy storage evaporation, (2) sublimation, (3) impervious storage evaporation, (4) evapotranspiration in the PRMS soilzone, and (5) transpiration below the PRMS soilzone. The available evapotranspiration at each step is the unsatisfied PET not used by other ET components (canopy-storage evaporation, sublimation, impervious-storage evaporation, transpiration, and soil-storage evaporation) after the previous computation step.

Aquifer Properties

Aquifer properties were assigned by parameters in the Upstream Weighting (UPW) Package (Niswonger and others, 2011) of the steady-state MODFLOW-NWT model to represent the horizontal hydraulic conductivity (K) along model rows, ratio of horizontal to vertical hydraulic conductivity (VANI), and ratio of hydraulic conductivity along model columns (dip direction of bedding) to hydraulic conductivity along model rows—the strike direction of bedding (HANI). Parameters for specific yield and specific storage also were specified for use in the transient GSFLOW model but were not needed for the MODFLOW-NWT steady-state simulation.

Ten parameters were used in the UPW package to represent the spatial distribution of hydraulic conductivity for the geologic units in the study area. Six parameters represent the groups of geologic units shown in table 7 (at end of report). Groupings of geologic units with similar hydraulic conductivity were based on previous studies, particularly the geologic mapping (fig. 5) and relative rankings by Parizek and Filey (1982) in table 7. Two additional parameters were used to represent zones of high horizontal hydraulic conductivity not restricted to a particular geologic unit. The parameter Kfract represents a zone of high hydraulic conductivity along the western margin of carbonate rocks in the Spring Creek Valley, and ThomK represents a similar zone of hypothesized high hydraulic conductivity near Thompson Run. Horizontal and vertical anisotropy with respect to hydraulic conductivity were assigned by parameters HANIcarb and VANI. Initially, all sandstone and shale units were assigned a hydraulic conductivity of 0.66 ft/d (0.2 m/d), and carbonate rocks were assigned 9.8 ft/d (3 m/d); then the values were adjusted during the model-calibration procedure.

Values of hydraulic conductivity for all parameters, except those representing the Mines Dolomite and upper sandy members of the Gatesburg Formation (Kgates), were assumed to decrease with depth because few high yielding fractures were reported below 300 feet, except in the Gatesburg Formation (Wood, 1980, p. 31). Values assigned to parameters in layer 1 were reduced in layer 2 by a factor of 0.2 for shale units and 0.7 for carbonate units. The hydraulic conductivity for all units in layer 3 was reduced by a factor of 0.04 from layer 1 values.

The ratio of horizontal to vertical hydraulic conductivity is specified by the parameter VANI, which was assigned a value of 1.0 for all geologic units in all layers. Its value was changed during model calibration only in a small area near Bellefonte, Pa., to control the quantity of groundwater discharge to the lower reaches of Logan Branch and Spring Creek. The ratio of hydraulic conductivity along model rows (along strike) to that along model columns (across strike) is specified by the parameter HANI. The value of HANI was adjusted during model calibration. Its value was computed as a base value multiplied by a factor ranging from 0.1 to 1.0 that represented the approximate effect of dipping beds on HANI. The factor was small for beds dipping steeply in the direction of model columns and was 1.0 for horizontal beds.

MODFLOW-Only Model Steady-State Calibration and Results

Aquifer properties in the MODFLOW-NWT model were adjusted by use of the parameter-estimation program UCODE-2005 (Poeter and others, 2005) and by trial and error. Values of hydraulic conductivity and horizontal anisotropy were adjusted by trying to match observations of average, steady-state, groundwater levels and computed base flow during water years 2000–06. The sources of groundwater levels and base flows used as observations for model adjustments are given in table 8. Locations of the wells used for groundwater-level data are shown in figure 13, and locations of streamgages used for base-flow computations are shown in figure 4.

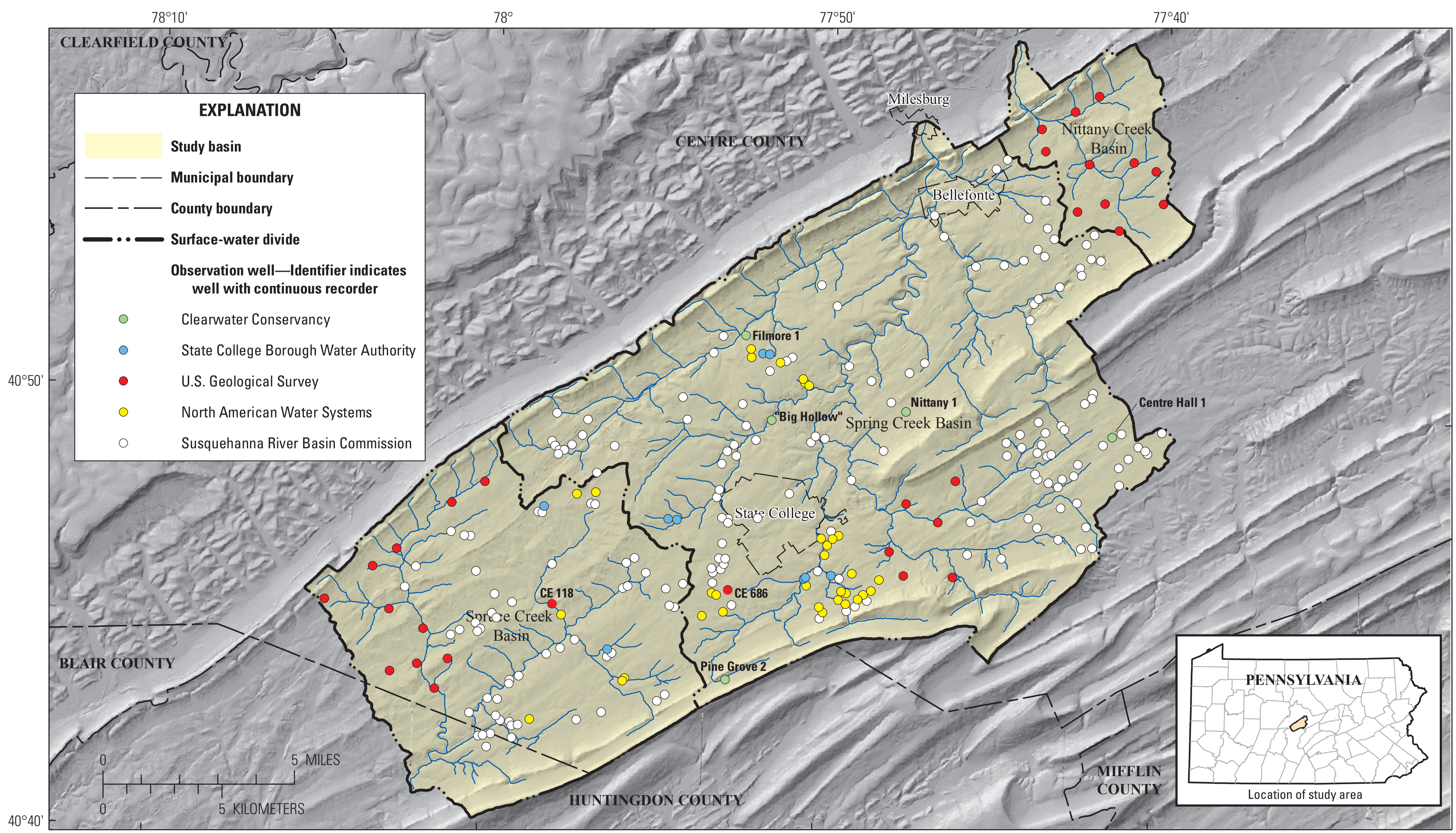
Groundwater-level observation data came from multiple sources. For wells with multiple groundwater levels, the mean value of the observations during water years 2000–06 was used. Groundwater levels from Taylor (1997) represent the largest synoptic dataset of groundwater levels, but they were measured during 1994, prior to the calibration period of this model. Regardless, because of its large areal coverage, the dataset was used, but the values were assigned a small weighting factor in the regression.

Base-flow observations used to adjust the model were either the base flow at a streamgage or the base-flow gain between two stations (table 9). Mean base-flow values for water years 2000–06 were computed for the local minimum

Table 8. Sources of streamflow data and groundwater levels used to adjust aquifer properties in the MODFLOW-NWT steady-state model for Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania.

[USGS, U.S. Geological Survey; USFWS, U.S. Fish and Wildlife Service; CWC, ClearWater Conservancy; SCBWA, State College Borough Water Authority; SRBC, Susquehanna River Basin Commission; NAWS, North American Water Systems; PSU, Penn State University; C, Continuous; D, Daily; CMP, Continuous with missing periods; P, Periodic; S, Single observations; --, none; X, missing record]

Streamgage name for stations used to compute base flow or source of groundwater levels	Station abbreviation	Agency	Type of observation	Missing record	Period of record
Streamflow data					
Spring Creek at Houserville, PA	SPH	USGS	C	--	10/1999–09/2006
Spring Creek near Axemann, PA	SPA	USGS	C	--	10/1999–09/2006
Spring Creek at Milesburg, PA	SPM	USGS	C	--	10/1999–09/2006
Spruce Creek at Graysville, PA	SPG	USFWS and USGS	D	X	10/1999–09/2006
Slab Cabin Run at Rt. 26 at Lemont, PA (Slab Cabin Run Lower)	SLL	CWC	C	X	10/1999–09/2006
Cedar Run at Oak Hall, PA (Cedar Run Lower)	CEL	CWC	C	X	10/1999–09/2006
Spring Creek at Oak Hall, PA (Spring Creek Upper)	SPU	CWC	C	X	10/1999–09/2006
Buffalo Run near Bellefonte, PA (Buffalo Run Lower)	BUL	CWC	C	X	10/1999–09/2006
Logan Branch near Pleasant Gap, PA (Logan Branch Upper)	LOU	CWC	C	X	10/1999–09/2006
Logan Branch above Big Spring at Bellefonte, PA (Logan Branch Lower)	LOL	CWC	C	X	02/2005–09/2006
Thompson Run near State College, PA (Thompson Run Lower)	THL	PSU	C	--	2007
Groundwater-level data					
7 observation wells	--	CWC and USGS	CMP	--	10/1999–09/2006
33 domestic-supply wells	--	NAWS	P	--	01/1999–06/2005
9 unused supply wells	--	SCBWA	P	--	01/2003–12/2004
180 domestic-supply wells	--	SRBC	S	--	October 1994
28 domestic-supply wells	--	USGS	S	--	1984



Base from U.S. Geological Survey digital data, 1972
Universal Transverse Mercator projection, Zone 18, NAD 1983
Streams from U.S. Geological Survey, National Hydrography Dataset, 2009
Shaded relief from PAMAP Program, 2008

Figure 13. Locations of groundwater wells with groundwater-level data used for calibrating the MODFLOW-NWT model for Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania.

Table 9. Base-flow values and weights used to adjust the MODFLOW-NWT steady-state model for Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania.

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

Station name[1]	Station abbreviation	Base-flow value (ft^3/s)	Weighting value [$ft/(ft^3/s)$]
Thompson Run Lower	THL	4.9	55.7
Cedar Run Lower	CEL	16.0	17.1
Logan Run Upper	LOU	21.0	13.0
Spring Creek Upper	SPU	19.0	14.4
Logan Run Lower	LOL	76.0	3.6
Slab Cabin Run Lower	SLL	10.7	25.5
Spruce Creek at Graysville, PA	SPG	38.0	5.4
Spring Creek at Houserville, PA	SPH	55.3	11.9
Buffalo Run Lower	BUL	14.0	19.5
Spring Creek—gain between Houserville and Axemann streamgages	AXE_GAIN	32.0	6.4
Logan Branch—between Upper and Lower streamgages	LOL_GAIN	55.0	2.7
Spring Creek—gain in main stem below streamgages near Axemann, PA and at Milesburg, PA	MILES_GAIN	20.0	10.3

[1]Slab Cabin Run Upper (SLU) and Buffalo Run Upper (BUU) were not included because of the uncertainty in the datasets.

method (Pettyjohn and Henning, 1979) by use of the HYSEP program (Sloto and Crouse, 1996). Because the streamflow record was not complete for some of the stations, daily streamflow values were estimated by using MISTE (MIssing STreamflow Estimation), a tool for estimating missing daily discharge values that relies on daily values that have been determined for other (index) sites (U.S. Geological Survey, 2003). The program uses stepwise regression analysis to correlate daily discharge data at the study site with daily discharge data from one or more index sites.

Weighting of Observations

A weighting factor was used in the parameter-estimation program UCODE to adjust observations to account for the difference in units between groundwater levels and base flows, and to incorporate differences in the perceived accuracy of observations. Weights for groundwater levels were assigned different values depending upon the accuracy of the measuring point elevation and frequency of groundwater-level observations. Groundwater levels measured once were assigned a lower weight than groundwater levels measured continuously and recorded for the study period. Weights assigned to groundwater levels ranged from 0.69 feet for discrete observations at 180 domestic-supply wells to 4.3 feet for the average groundwater level for the study period at seven observation wells with continuous recorders. Weights for base-flow observations relied on the estimated accuracy of the streamflow record compiled by USGS, CWC, and others, as described in Hill and Tiedeman (2007, p. 291). All base-flow weights were then increased by a factor of 100 to yield weighted residuals that were in the same range as the groundwater-level residuals. The greater weights increased the weighted residuals and importance of the base-flow observations in the parameter estimation process. The base-flow weighting values are shown in table 9.

Adjusted Aquifer Properties

Aquifer properties were adjusted during model calibration, and the final values for each parameter are given in table 10. Horizontal hydraulic conductivity zones for layers 1 to 3 are illustrated in figures 14, 15, and 16, and values for areas of horizontal anisotropy applicable to all layers are shown in figure 17. The storage properties of the aquifer—specific storage and specific yield—were not adjusted during steady-state MODFLOW-NWT simulations because those parameters were not applicable. Storage properties were needed for transient GSFLOW simulations, so they were adjusted from their initial assigned values during GSFLOW calibration. Specific storage was initially assigned a value of 0.3048E-6 per foot (1.0 E-6 per meter) in all layers; the initial distribution of specific-yield values is illustrated in figures 18 and 19.

During model calibration, results were not sensitive (composite scaled sensitivity of less than 0.4) to the ratio of horizontal to vertical hydraulic conductivity (VANI) so its value was set to 1.0 and was only adjusted beneath the lower reaches of Spring Creek and Logan Run. For example, beneath Spring Creek, VANI was increased to 100; and beneath Logan Run, it was decreased to 0.01 in order to increase the groundwater discharge to Logan Run in a reach of known large stream gains and to reduce the simulated discharge to Spring Creek near Houserville.

To simulate the groundwater trough along the northwestern side of the study basin, a zone of large hydraulic conductivity was inserted into layer 2 (parameter Kfract in table 10 and fig. 15) to depress simulated groundwater levels in the area of the trough. The axis of the trough trends northeast-southwest, parallel to model rows. Formation of the trough has been explained as an expression of a zone of large hydraulic conductivity associated with the Birmingham Thrust Fault (Siddiqui, 1969, p. 404; Parizek and others, 1971, p. 36). The water-table configuration simulated by the model is shown in figure 20. An area of large hydraulic conductivity was also simulated in layer 1 near Thompson Run (parameter ThomK in table 10 and fig. 14) to allow the groundwater flow to discharge to that stream in quantities indicated by the streamgage.

Spatial differences in hydraulic conductivity with depth are illustrated in a section across the study basin along model column 119 at the nose of Nittany Mountain (fig. 21). Note the decrease in hydraulic conductivity with depth and the large hydraulic conductivity cell in layer 2 representing the highly permeable fracture (shown in red).

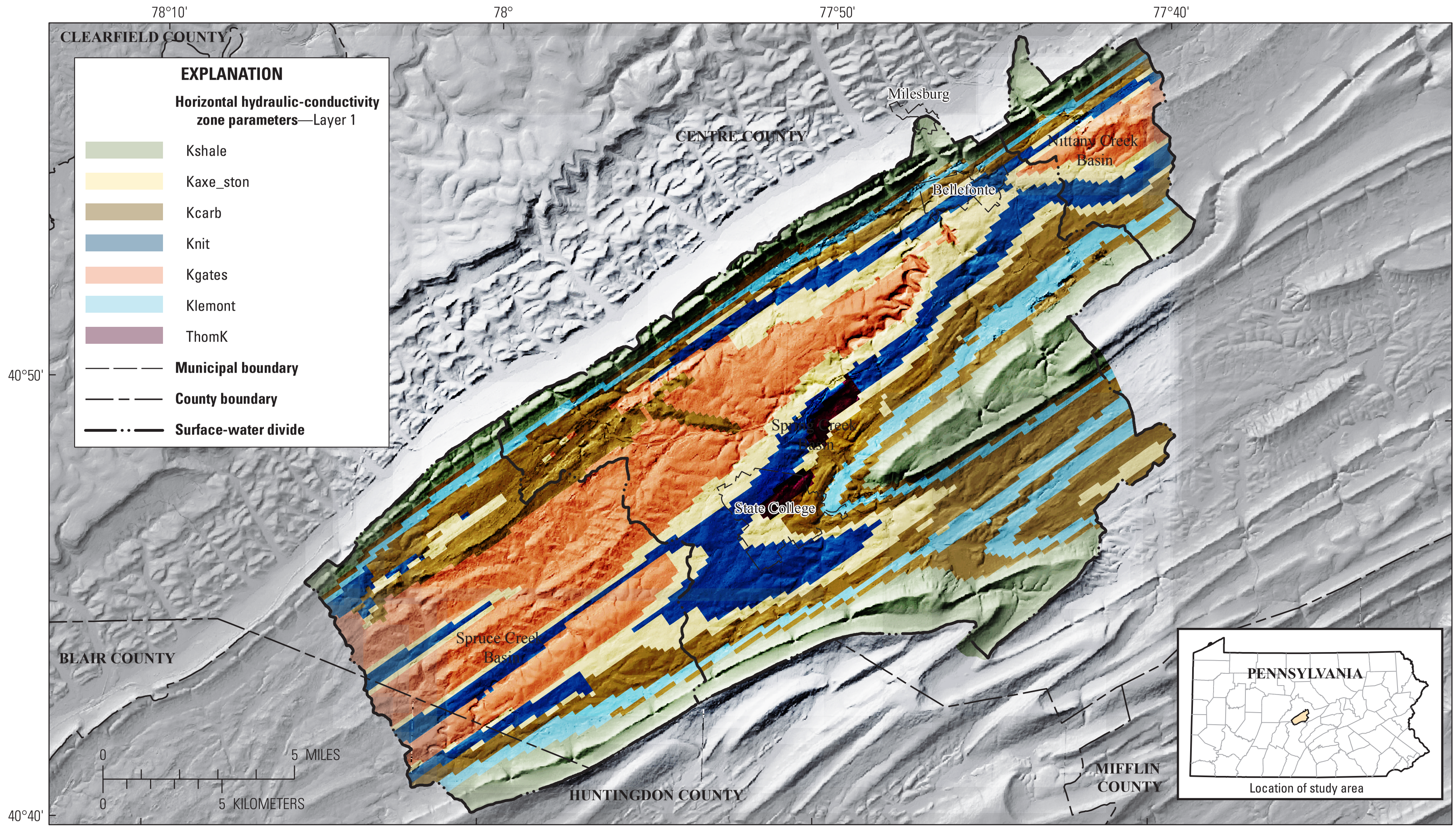
Table 10. Adjusted values and sensitivities of parameters used in the steady-state MODFLOW-NWT model for Spring Creek and Nittany Creek Basins and Parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania.

Formation parameter name	Adjusted value of horizontal hydraulic conductivity along rows (feet/day)	Composite scaled sensitivity
Kshale	0.26	1.2
Kcarb	9.0	1.8
Kgates	61.0	2.4
Knit	33.1	1.9
Kfract	1,417	3.9
Kaxe_ston	3.4	0.69
ThomK	1,247	1.9
LemontK	60.4	1.6
Formation parameter name	**Adjusted ratio of horizontal anisotropy along columns to along rows (dimensionless)**	**Composite scaled sensitivity**
HANIcarb	0.33	2.78

Comparison of Simulated and Observed Steady-State Groundwater Levels and Base Flows

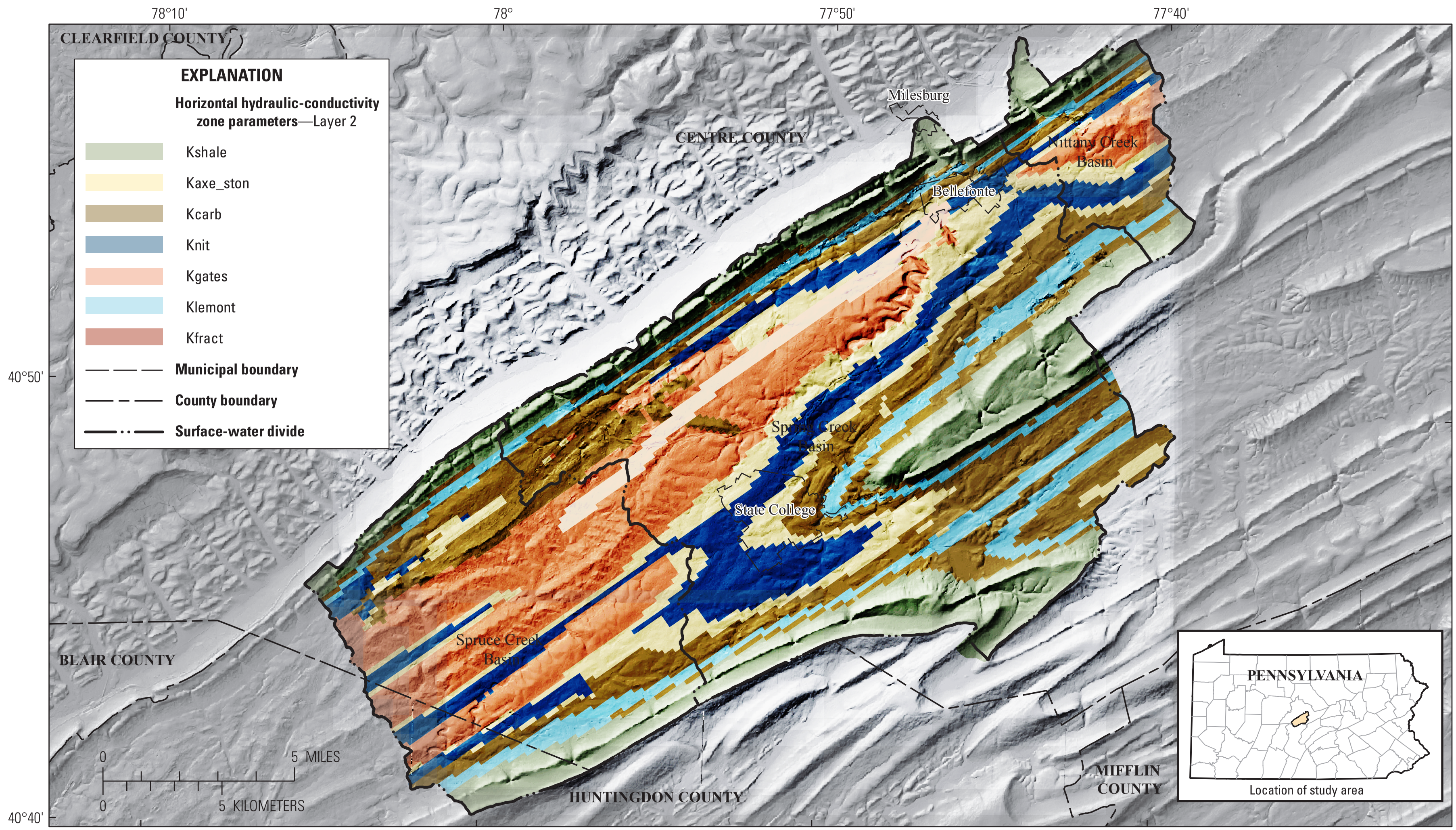
Steady-state groundwater levels simulated by the model were compared to groundwater levels from 257 wells (fig. 22). There is considerable scatter associated with the data. The root mean squared difference (RMSD) is 43 ft, and RMSD normalized to the range of groundwater-level observations is 5.1 percent. About 72 percent of the simulated groundwater levels were within 40 ft of the observed values. However, for the wells with surveyed measuring points [levels provided by Spring Creek Watershed Community (SCWC), N.A. Water Systems, and SCBWA], 96 percent of the residuals were less than 40 ft. Simulated groundwater levels were lower than observed levels at 39 percent of the observations, so the model more frequently simulated levels that were too high rather than too low. Simulated groundwater levels with the greatest error tended to be those for single groundwater-level observations from the Susquehanna River Basin Commission (SRBC) and USGS sources. Those observations were historical in nature made many years prior to the simulation period and, for the SRBC sources, were only approximately located on the land surface. For these reasons, observations from those datasets were assigned low weights in the overall parameter estimation.

Steady-state base-flow values simulated by the model were compared to base flows computed from streamflow at 16 sites in figure 23. Three of the 16 base-flow values were for the base-flow gains between streamgages on Spring Creek. The simulated values are biased low and are less than the base-flow estimates at most locations. The low values of simulated base flow were caused by an insufficient application of infiltration to the unsaturated zone (UZF package) of the MODFLOW-NWT model. Because the infiltration was derived from output of the calibrated PRMS model, infiltration values were not increased in MODFLOW. The infiltration rates were estimated independently during calibration of the coupled GSFLOW model.



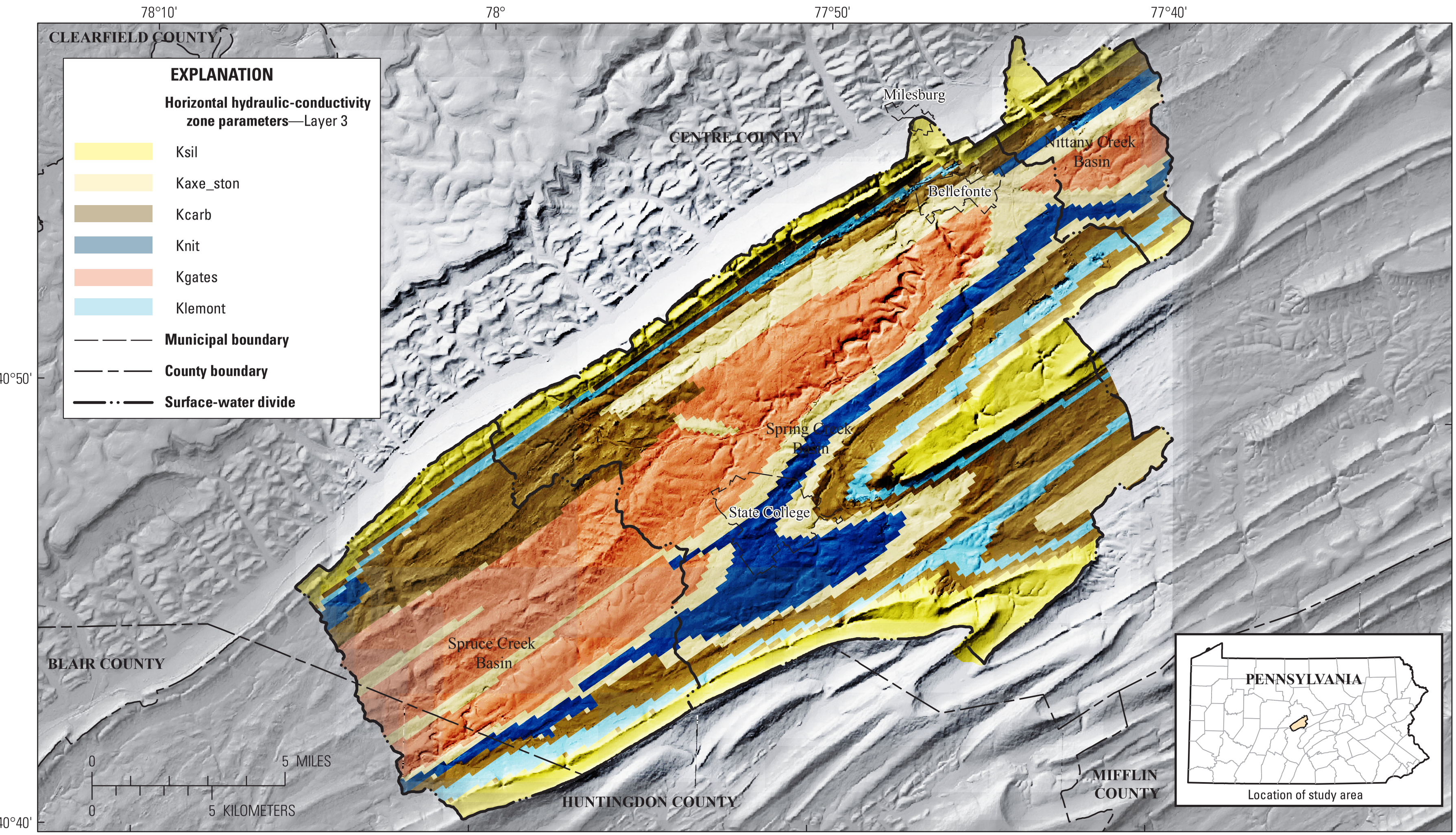
Base from U.S. Geological Survey digital data, 1972
Universal Transverse Mercator projection, Zone 18, NAD 1983
Shaded relief from PAMAP Program, 2008

Figure 14. Horizontal hydraulic conductivity zone parameters for layer 1 of the MODFLOW-NWT model for Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania.



Base from U.S. Geological Survey digital data, 1972
Universal Transverse Mercator projection, Zone 18, NAD 1983
Shaded relief from PAMAP Program, 2008

Figure 15. Horizontal hydraulic conductivity zone parameters for layer 2 of the MODFLOW-NWT model for Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania.



Base from U.S. Geological Survey digital data, 1972
Universal Transverse Mercator projection, Zone 18, NAD 1983
Shaded relief from PAMAP Program, 2008

Figure 16. Horizontal hydraulic conductivity zone parameters for layer 3 of the MODFLOW-NWT model for Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania.

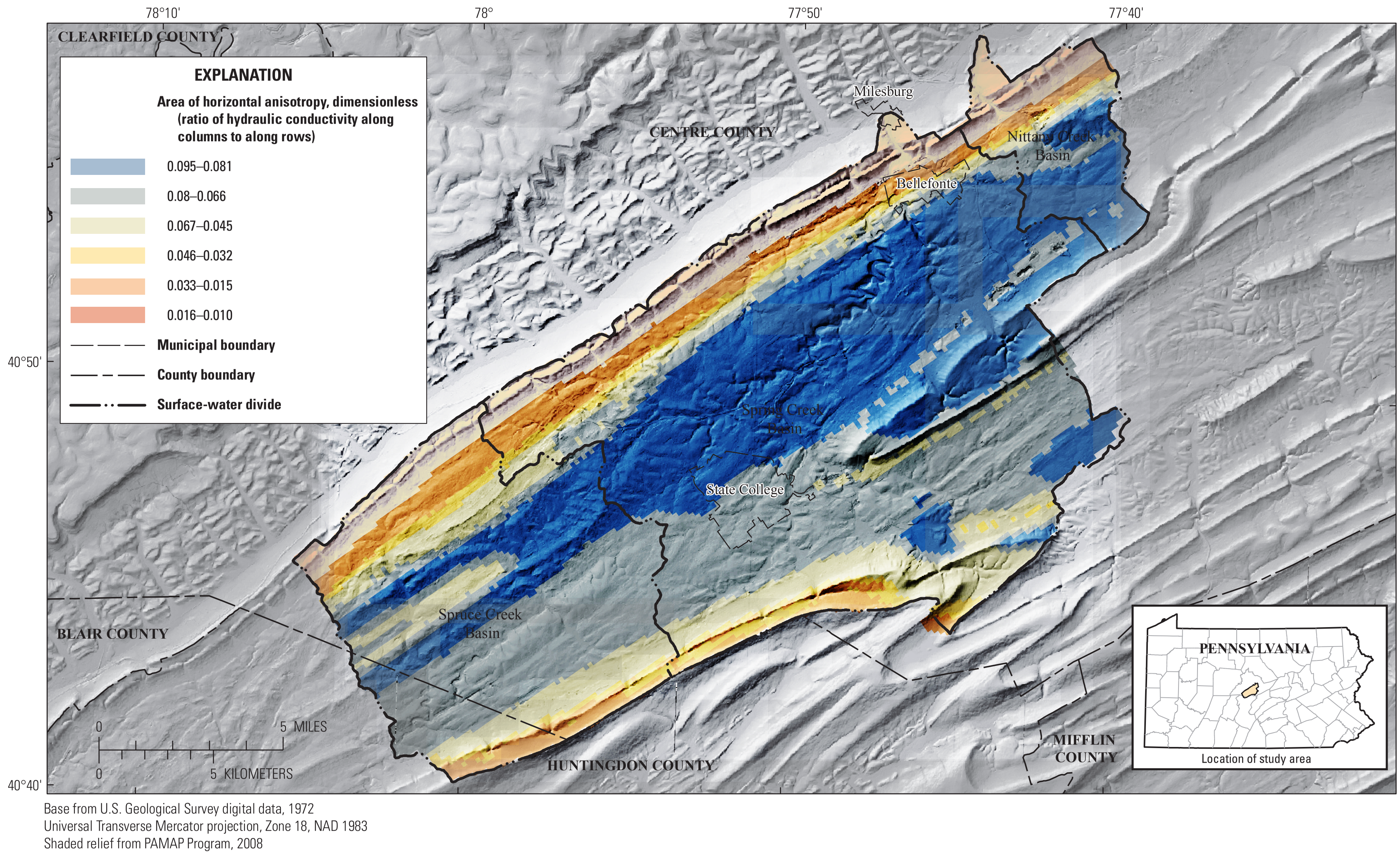
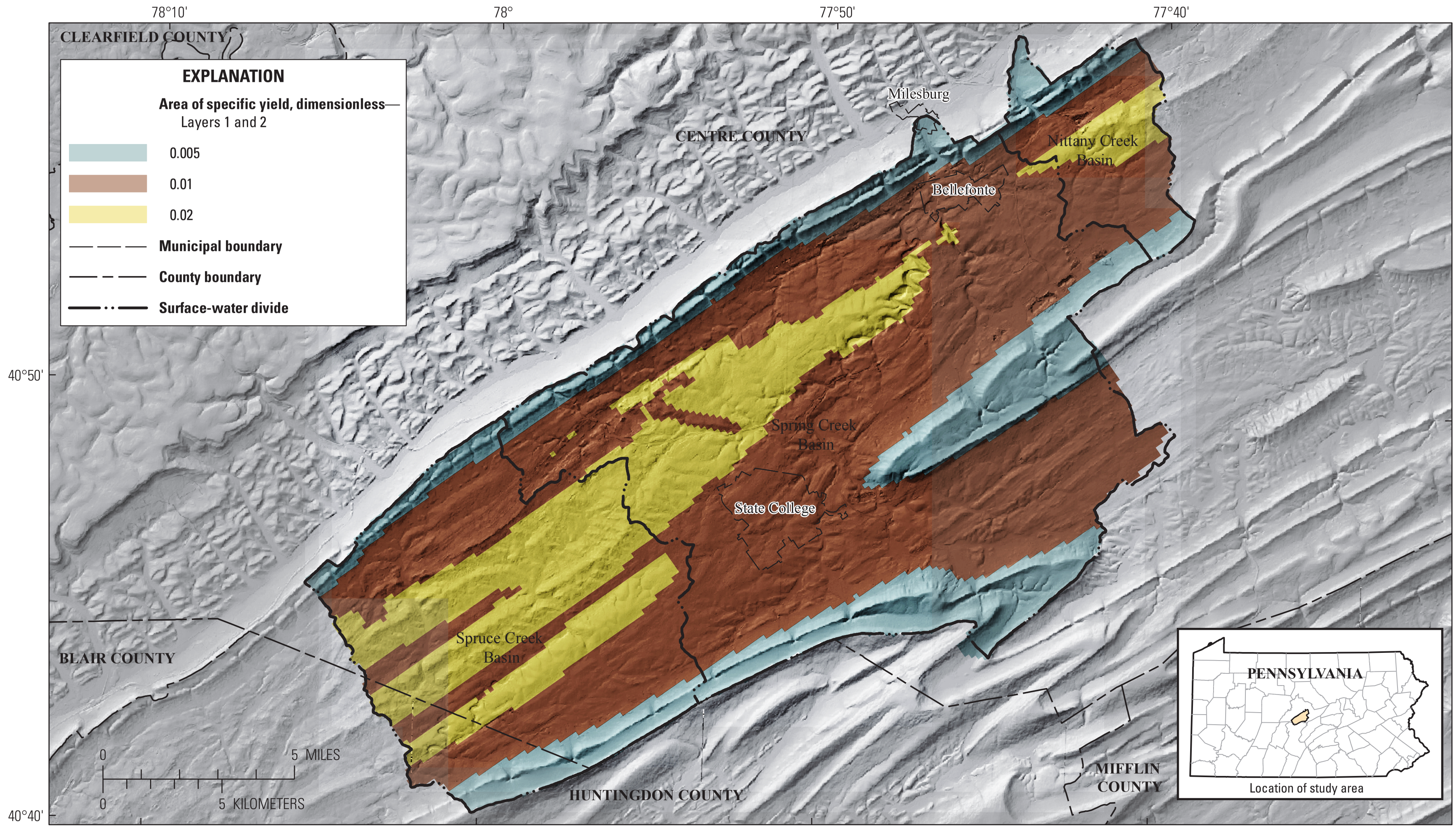
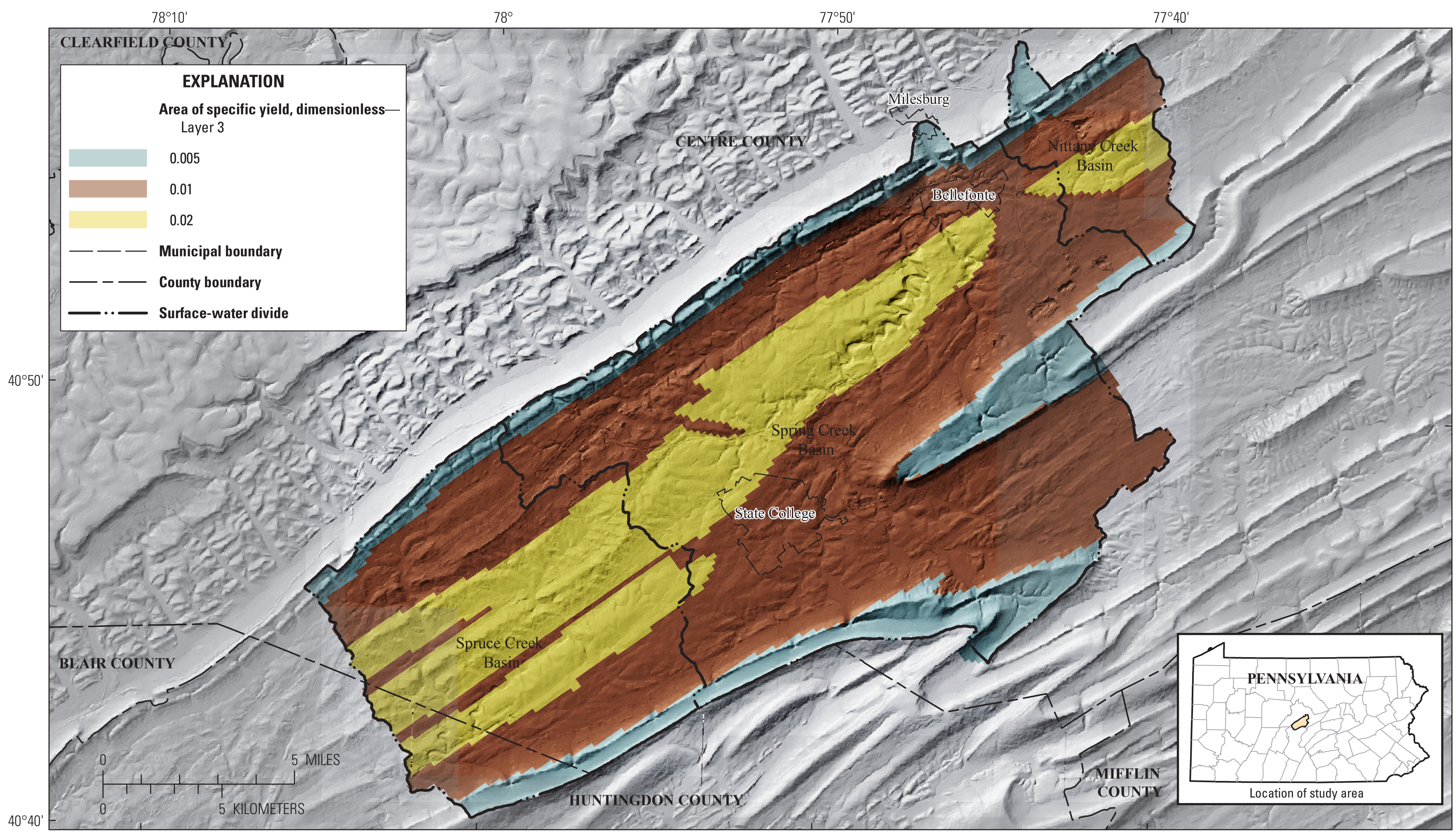


Figure 17. Areas of horizontal anisotropy in layer 1 of the MODFLOW-NWT model for Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania.



Base from U.S. Geological Survey digital data, 1972
Universal Transverse Mercator projection, Zone 18, NAD 1983
Shaded relief from PAMAP Program, 2008

Figure 18. Areas of specific yield in layers 1 and 2 of the MODFLOW-NWT model for Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania.



Base from U.S. Geological Survey digital data, 1972
Universal Transverse Mercator projection, Zone 18, NAD 1983
Shaded relief from PAMAP Program, 2008

Figure 19. Areas of specific yield in layer 3 of the MODFLOW-NWT model for Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania.

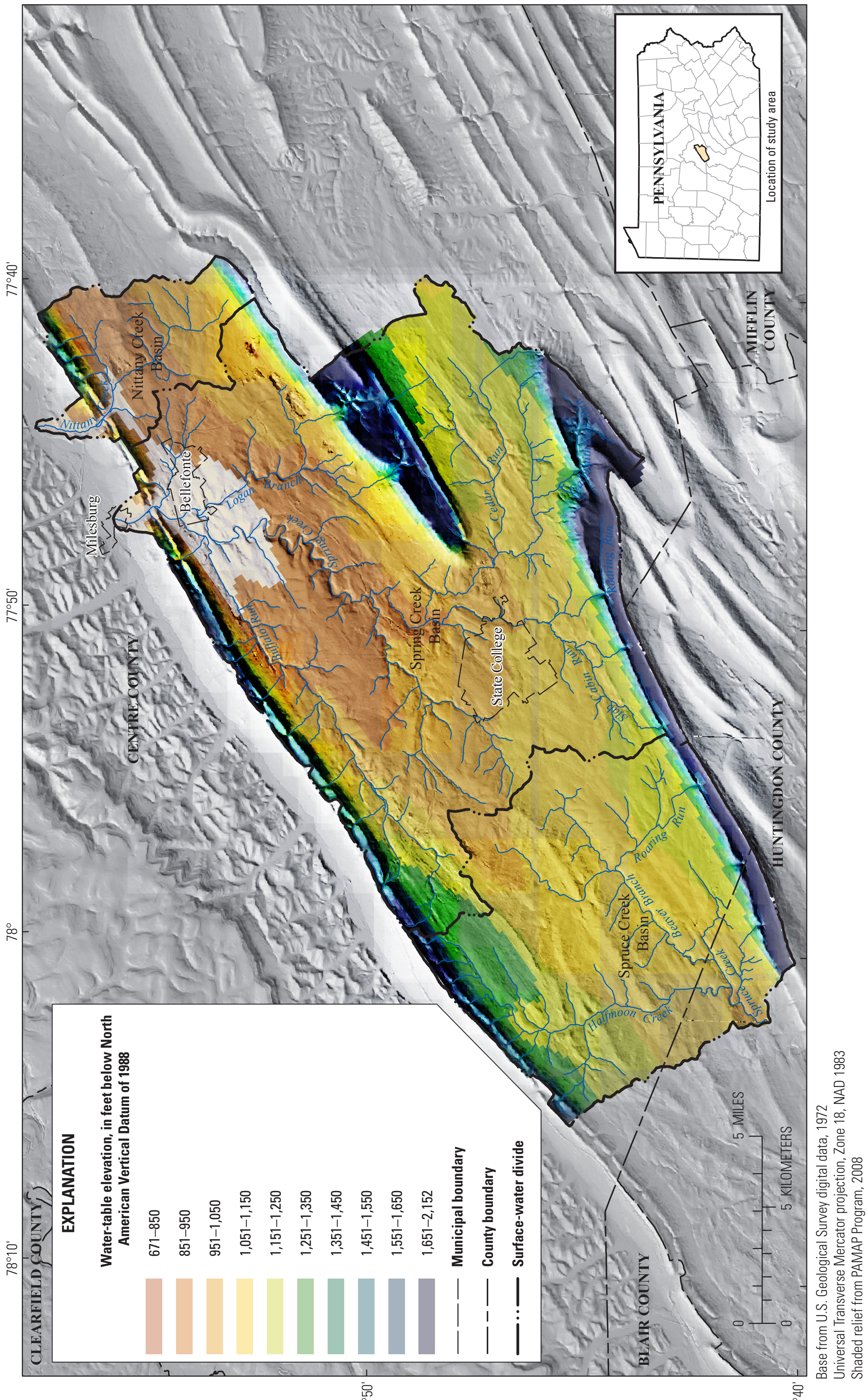


Figure 20. Water-table elevations simulated by the MODFLOW-NWT model for Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania.

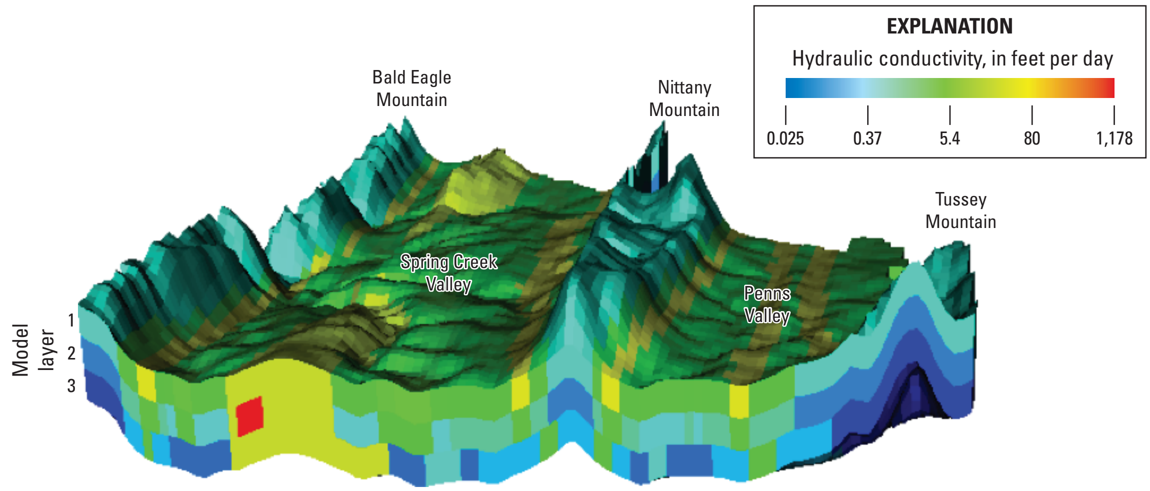


Figure 21. Hydraulic conductivities through column 119 of the MODFLOW-NWT model for Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania.

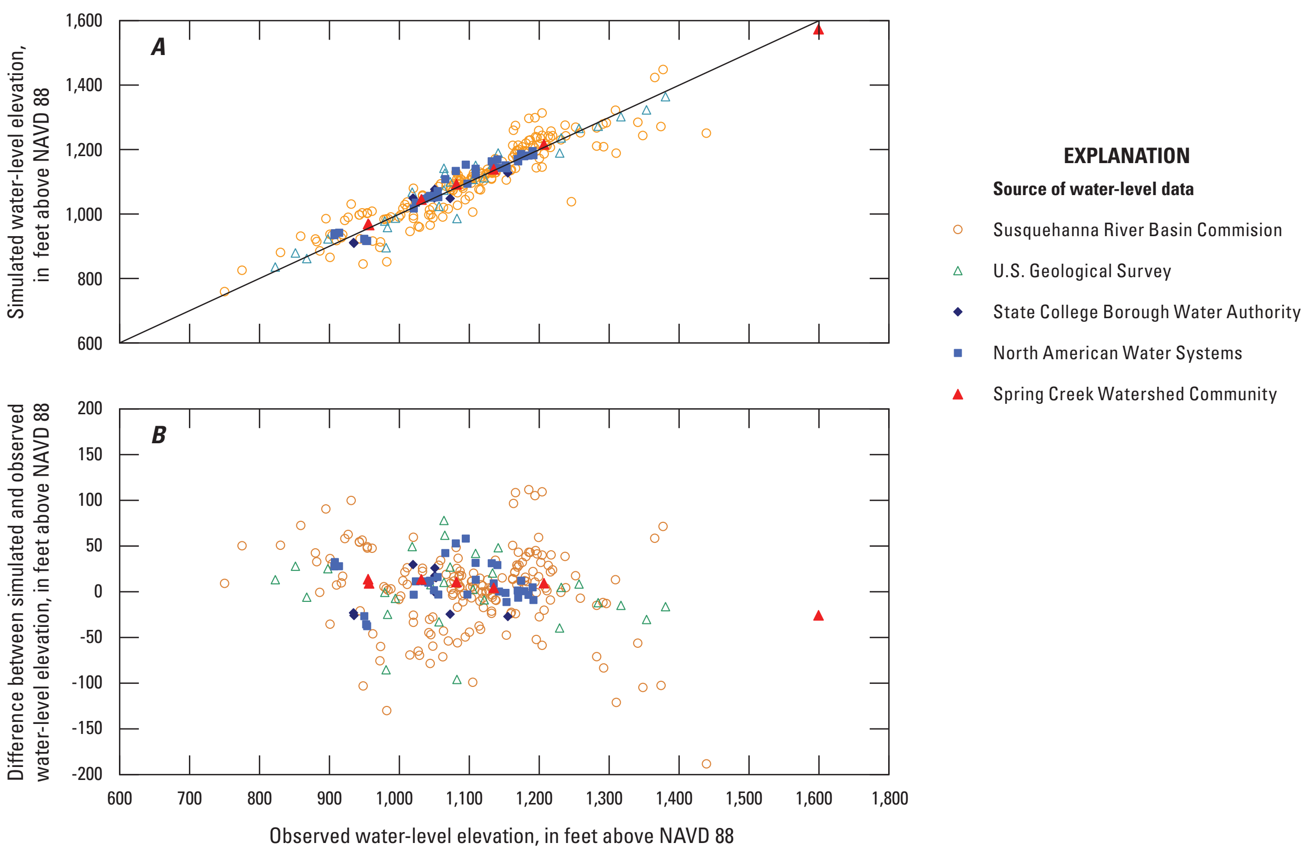


Figure 22. Observed steady-state groundwater levels in relation to *A*, MODFLOW-NWT simulated elevations and *B*, the difference between simulated and observed elevations for 257 wells in Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania.)

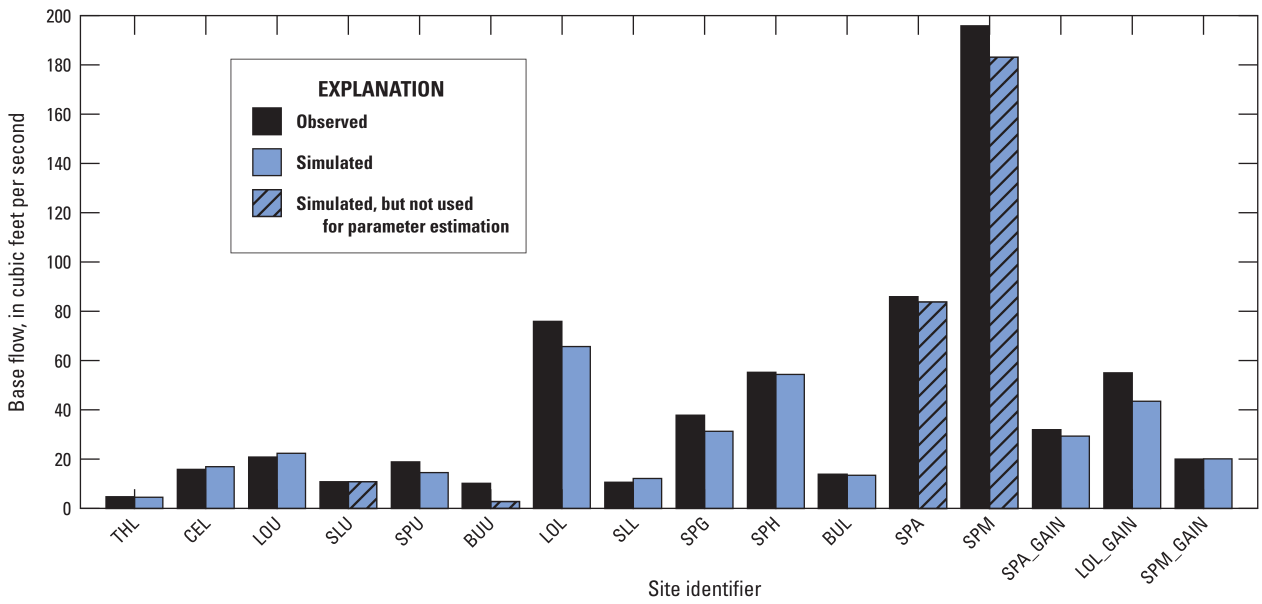


Figure 23. Observed steady-state base flows and steady-state base flows simulated by the MODFLOW-NWT model at 16 sites in Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania, water years 2000–06. See tables 8 and 9 for description of site identifiers.

Calibration of the Hydrologic Model and Simulation Results

Surface-water and groundwater budgets were calculated for daily time steps in GSFLOW. Results from the GSFLOW model are reported for water years 2000–06, but the simulation period included the 3-years prior to water year 2000, which provided time for the simulated hydraulic system to adjust from the initial conditions that were assigned to the model.

Calibration of the GSFLOW model was conducted in three steps. First, the parameters of the PRMS rainfall-runoff model and MODFLOW-NWT groundwater models were adjusted separately as stand-alone simulations that were not linked. Next, the simulated infiltration rates from PRMS were added to the MODFLOW-NWT model, and the MODFLOW-NWT input parameters were readjusted using professional judgement and UCODE. Finally, after these preliminary adjustments, the separate models were linked in the GSFLOW code, and the parameters of both models were adjusted together for a final calibration by using the parameter estimation software PEST (Doherty, 2010, see http://pesthomepage.org for description of PEST). Hydrologic processes were computed in a fixed computation sequence that included four procedures as described in Markstrom and others (2008).

Parameter Estimation with PEST

In addition to issues of parameter insensitivity and correlation of observation data for constraining a coupled model, there are also concerns with measurement noise and redundant information in the large number of transient observations used to calibrate the fully coupled model. This is a primary concern here because areal surface-water data sets typically include many observations, especially with respect to the temporal density of the observations in a spatially distributed network; many of these data carry redundant insight into the system, but each contributes to the measurement noise that is encountered during calibration. In order to enhance the signal-to-noise ratio within the observation data, a time-series processing approach to the time-series observations was employed whereby the raw observations were processed and distilled into characteristic aspects of the system (Westenbroek and others, 2012). The simulated GSFLOW output was then processed in the same way as the raw observations and compared directly in the parameter estimation process. The processing was performed by using the Time-Series Processor TSPROC (Doherty, 2008;

Westenbroek and others, 2012). TSPROC has the ability to read and process native PRMS and MODFLOW-NWT output files.

Calibration Approach

Whereas the sequentially linked calibration used representative steady-state water levels for groundwater model calibration, the fully coupled model is transient on a daily time step. Therefore, the time-series groundwater-levels measured during the study were included in the coupled model. In addition to the daily or intermittent values, the annual mean groundwater-levels were used for calibration.

In addition to the groundwater-level data, the following streamflow calibration targets were processed:

1. **Log of daily streamflow**—the natural log of daily streamflow was used to mitigate the undue influence of extremely high daily discharges on the calibration,
2. **Annual mean streamflow**—the average streamflow for each water year during the simulation period and represents the streamflow portion of the annual hydrologic budget,
3. **Monthly mean streamflow**—the average streamflow for each month during the simulation and represents the total monthly volume of streamflow,
4. **Mean monthly streamflow**—the streamflow for each month averaged over the entire simulation period and represents the seasonal variation of streamflow, and
5. **Monthly mean base flow**—the average base flow for each month during the simulation and represents the groundwater contribution to streamflow.

Because forward run times for the fully coupled model were multiple hours long, all parameters varied during the separate PRMS and MODFLOW-NWT calibrations could not be evaluated in the fully coupled model calibration. Thus, it is possible that undesirable artifacts from the uncoupled model calibration may not be completely addressed in the coupled model calibration. After some initial calibration tests, the final fully coupled model was calibrated by using the selected set of parameters listed in table 11. Some parameters not available in the steady-state MODFLOW-NWT-only calibration (for example, aquifer storage), parameters important for simulating the interface between the MODFLOW-NWT only and PRMS-only models, and parameters having utility for calibration of the coupled model (for example, vertical hydraulic conductivity of the unsaturated zone) were included. All but three of the parameters were used for final calibration control routing of infiltrated water through the subsurface; those three parameters affect precipitation storage in the form of snow. The fully coupled model calibration used singular value decomposition on the entire base parameter set. Of these parameters, the information content of the multi-objective function observation data supported approximately linear combinations of the base parameters (singular values) by using stability criteria (PEST variable EIGTHRESH= 5.0 x 10^7) proposed by Doherty and Hunt (2010).

Observation Weights

In general, an estimate of uncertainty in the streamflow observations was used as a starting point for the weights for each observation group. The weight (w_g)was assigned to be the reciprocal of the uncertainty for each group (σ_g); thus,

$$w_g = \frac{1}{\sigma_g} \; .$$

The uncertainties were estimated by using the coefficient of variation (standard deviation divided by the mean) and an average value for each observation group. Thus, the weight is estimated as

$$w_g = \frac{1}{\mu_g CV_g} \; ,$$

where μ_g and CV_g are the mean and coefficient of variation of the observations for the group, respectively. For a log-transformed normally distributed variable, the standard deviation in log space was determined by rearranging the equations relating log-space (y) moments to real-space (x) moments (Miller and Freund, 1977):

$$\sigma_y = \sqrt{\log(1 + CV_x^2)} \; .$$

Because the groups contained observations at different time scales, there was a considerable difference in the number of observations within each group and from station to station. To compensate for the number of observations, the weights were adjusted to represent an equivalent number of annual, monthly, and mean monthly observations. This reasoning follows from the basic identity that the standard deviation of the mean (m) from a random sample of size n is given by

$$\sigma_m = \frac{\sigma_g}{\sqrt{n}} \; .$$

Because the weights are equal to the inverse of the standard deviation, the weight for a mean statistic becomes

$$w_m = \frac{1}{\sigma_m} = \frac{\sqrt{n}}{\sigma_g} = w_g \sqrt{n} \; .$$

The UCODE weights for the steady-state MODFLOW-NWT calibration were used as a starting point for the weights for the fully coupled calibration. On the basis of experimentation, it was determined that the initial weights for the water-level data needed to be adjusted to assure that the water-level data were seen in the resulting objective function. The final non-zero weights used for the water-level data are given in table 12. The water-level data for well CE118 (fig. 13) was set to 0.0 in the final calibration, which removes the observation

Table 11. Parameters used in the calibration of the coupled model for Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania.

[PRMS, Precipitation-Runoff Modeling System]

PRMS parameter name	Description of PRMS parameter	Default value	Lower bound	Upper bound	Average calibrated parameter	Minimum calibrated parameter	Maximum calibrated parameter
adjmix_rain	Adjustment factor for rain in a rain/snow mix (decimal fraction)	1	0	3	1.0644	0.6	1.4
fastcoef_lin	Linear preferential-flow routing coefficient (1/day)	0.1	0	1	0.0107	0.0004	0.2452
rain_sub_adj	Rain adjustment factor for each subbasin and each month (decimal fraction)	1	0	4	1.0571	0.8	1.2
sat_threshold	Soil saturation threshold, above field-capacity threshold (inches)	999	1	999	5.3311	1	14.9996
slowcoef_lin	Linear gravity-flow reservoir routing coefficient (1/day)	0.015	0	1	0.012	0.001	0.1395
smidx_coef	Coefficient in contributing area computations (decimal fraction)	0.01	0.0001	1	0.0049	0.0007	0.0263
snow_sub_adj	Snow adjustment factor for each subbasin and each month (decimal fraction)	1	0	4	1.1	1	1.2
soil_moist_max	Maximum value of water for soil zone (inches)	6	0	20	5.8882	2	10
soil_rechr_max	Maximum value for soil recharge zone (inches)	2	0	10	1.1107	0.7018	1.4658
soil2gw_max	Maximum value for soil water excess to groundwater (inches)	0	0	5	0.0683	0	0.5
ssr2gw_rate	Coefficient to route water from subsurface to groundwater (1/day)	0.1	0	1	0.1159	0.05	0.7364

MODFLOW parameter name or multiplier	Description of MODFLOW parameter or multiplier	Calibrated value
Kshale Kcarb Kgates Knit Kfract Kaxe_ston ThomK LemontK	Horizontal hydrologic conductivity value along rows in model layer 1 for geologic units assigned to each parameter in table 7 (feet/day)	0.07887 10.52024 75.41289 27.29462 2,430.89140 11.31514 1,493.16273 60.71178
HANIcarb	Ratio of horizontal hydraulic conductivity along columns to along rows for carbonate-rock aquifers in table 7 (dimensionless)	0.10305
vani	Ratio of horizontal to vertical hydraulic conductivity (dimensionless)	0.70002
sycarb	Specific yield of all carbonate-rock units in table 7 except the upper sandy and Mines Members of the Gatesburg Formation (dimensionless)	0.01287
sygates	Specific yield of the upper sandy and Mines Members of the Gatesburg Formation in table 7 (dimensionless)	0.18254
sysil	Specific yield of siliciclastic aquifers in table 7 (dimensionless)	0.05000
surfdep	Average undulation depth of the soil-zone base elevation (feet)	2.12507
kmult_lay2 kmult_lay3	Multiplication factors for multiplier arrays of hydraulic conductivity values in layers 2 and 3 (dimensionless)	2.00000 1.67659
vani_mult	Multiplication factor for multiplier array of the ratio of horizontal to vertical hydraulic conductivity (dimensionless)	1.56919
hani_mult	Multiplication factor for multiplier array for the ratio of horizontal hydraulic conductivity along columns to along rows (dimensionless)	0.76602
ss1 ss2 ss3	Specific storage multiplier for arrays of specific-storage values for all parts of layers 1, 2, and 3 (dimensionless)	0.89850 0.80800 1.12800
vksat	Multiplier for the array of saturated vertical hydraulic conductivity in the unsaturated zone (dimensionless)	0.94377

from consideration for the evaluation of model fit because it was causing instability in estimation of parameters; therefore, well CE118 is not listed in table 12. The final non-zero weights for the streamflow data are given in table 13. The streamflow data for upper Buffalo Run (BUL) and Thompson Run (THL) were zeroed out in the final calibration and, thus, are not shown in table 13.

Comparison of Simulated Results with Observations

Simulated values of streamflow and groundwater levels from GSFLOW are compared to observations from 11 streamgages and 16 wells for water years 2000–06 in figures A1–A14 (see appendix). Model results are compared to calibration targets of the natural log of daily mean streamflow (fig. A1); annual streamflow, monthly mean streamflow, monthly mean base flow, and mean monthly streamflow (figs. A2–A12); and groundwater levels and annual mean groundwater-levels in observation wells (figs. A13–A14).

Simulated and observed results are compared graphically and with the Nash-Sutcliffe coefficient. The Nash-Sutcliffe coefficient is a widely used statistic to describe the accuracy of model simulations (Nash and Sutcliffe, 1970). The coefficient can vary between 1 and negative infinity, with 1 representing a perfect correspondence between simulated and observed values and values less than zero indicating that the mean value of the observations is a better predictor than the model results. Although the Nash-Sutcliffe coefficient has biases that affect the magnitude of the statistic, Moriasi and others (2007) consider a coefficient of greater than 0.5 to be one indicator of acceptable model performance.

Streamflow and Base Flow

Comparison of model simulations to observed values for the calibration targets indicates the calibrated GSFLOW model represents an acceptable simulation of streamflow and base flow for most sites, as shown graphically (figs. A1–A12) and by Nash-Sutcliffe coefficients that were generally greater than 0.5. The exception was for the site Buffalo Run Lower where Nash-Sutcliffe coefficients were less than 0.5 for most of the calibration targets. The Nash-Sutcliffe coefficients for the streamflow and base-flow calibration targets are summarized in table 14.

Simulations of daily streamflow are considered acceptable for most sites (fig. A1). The model fit to daily streamflow was best (Nash-Sutcliffe coefficients of 0.70 and 0.73) for Spring Creek at Milesburg and for Spruce Creek at Graysville, respectively. Those two streamgages measured the major outflows from the study basin. Overall, simulation of streamflow appeared to be poorest for Buffalo Run Lower as indicated by Nash-Sutcliffe coefficients of less than 0.5 for most of the calibration targets. Simulation of low streamflows at Buffalo Run Lower seemed most problematic, which was also was the case at Logan Run Upper, and at the two streamgages on Slab Cabin Run. These streams have substantial losing reaches during low-flow periods, which probably are not being adequately simulated.

The simulations of annual mean streamflow (graph A in figs. A2–A12) are considered acceptable (Nash-Sutcliffe coefficients 0.65 to 0.96), except at the gaging station Buffalo Run Lower (Nash-Sutcliffe coefficient 0.41). During wet years of high streamflow, the model slightly overestimated annual streamflow at most sites, and during dry years streamflow generally was slightly underestimated. However, at streamgages Spring Creek Upper and Spruce Creek at Graysville, simulations underestimated annual streamflow for all years except for water year 2006, the last year of the simulation. The underestimates of streamflow at these sites are probably caused by simulating too much groundwater underflow from these subbains.

Table 12. Final weights used for groundwater-level data in the PEST transient calibration of the coupled model for Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania.

Well name	Weight[1]
Continuous groundwater levels	
BIG HOLLOW	2.60
CE686	1.25
CENTRE HALL	2.60
FILMORE1	2.60
NITTANY	2.60
PINEGROVE 2	1.25
Intermittent groundwater levels	
CE 446	1.25
CE 690	1.25
CE 691	1.25
CE 692	1.25
CE 693	1.25
CE 694	1.25
CE 695	1.25
CE 696	1.25
CE 697	2.60
CE 698	2.60
Annual mean groundwater levels	
CE 446	1.25
CE 690	1.25
CE 691	1.25
CE 692	1.25
CE 693	1.25
CE 694	1.25

[1]Higher weight equals higher importance in the parameter estimation.

Table 13. Final weights used for the streamflow data in the PEST transient calibration of the coupled model for Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania.

Stream name	Weight
Log of daily streamflow	
Buffalo Run lower	2.53811
Cedar Run lower	2.53811
Logan Run lower	2.53811
Logan Run upper	2.53811
Slab Cabin Run lower	2.53811
Slab Cabin Run upper	2.53811
Spring Creek at Houserville	6.07350
Spring Creek at Milesburg	6.07350
Spring Creek near Axemann	6.07350
Spring Creek upper	2.53811
Spruce Creek at Graysville	1.90883
Annual average streamflow	
Buffalo Run lower	22.75233
Cedar Run lower	19.90946
Logan Run lower	4.19137
Logan Run upper	15.16822
Slab Cabin Run lower	29.69118
Slab Cabin Run upper	0.00093
Spring Creek at Houserville	13.84030
Spring Creek at Milesburg	0.00012
Spring Creek near Axemann	0.00028
Spring Creek upper	16.76733
Spruce Creek at Graysville	6.28705
Monthly average streamflow	
Buffalo Run lower	6.56803
Cedar Run lower	5.74736
Logan Run lower	1.20994
Logan Run upper	4.37869
Slab Cabin Run lower	8.57111
Slab Cabin Run upper	0.00027
Spring Creek at Houserville	3.99535
Spring Creek at Milesburg	0.00004
Spring Creek near Axemann	0.00008
Spring Creek upper	4.84031
Spruce Creek at Graysville	1.81491

Stream name	Weight
Monthly average base flow	
Buffalo Run lower	6.56803
Cedar Run lower	5.74736
Logan Run lower	1.20994
Logan Run upper	4.37869
Slab Cabin Run lower	8.57111
Slab Cabin Run upper	0.00027
Spring Creek at Houserville	3.99535
Spring Creek at Milesburg	0.00004
Spring Creek near Axemann	0.00008
Spring Creek upper	4.84031
Spruce Creek at Graysville	1.81491
Mean monthly streamflow	
Buffalo Run lower	17.37738
Cedar Run lower	15.20610
Logan Run lower	3.20121
Logan Run upper	11.58492
Slab Cabin Run lower	22.67701
Slab Cabin Run upper	0.00071
Spring Creek at Houserville	10.57070
Spring Creek at Milesburg	0.00009
Spring Creek near Axemann	0.00021
Spring Creek upper	12.80626
Spruce Creek at Graysville	4.80181

The simulations of monthly mean streamflow (graph B in figs. A2–A12) are acceptable (Nash-Sutcliffe coefficients 0.75 to 0.92), except at Buffalo Run Lower. The timing and magnitude of the simulated monthly mean streamflow corresponds reasonably well to the observed streamflow. During dry periods of low flow, the fit of simulated to observed monthly mean streamflow was better than the fit to daily flow for the same periods.

Mean monthly streamflow is the mean of all monthly mean flows for a particular month for the 7-year simulation period. Simulated values of mean monthly streamflow are shown in graph D (figs. A2–A12), where observation numbers 1 through 12 correspond to months of the calendar year. Comparisons of simulated and observed mean monthly flow highlight the seasonal errors in flow that are difficult to notice in graphs of daily or monthly mean streamflow. At seven of the streamgages, simulations underestimated high flows in March and April. At four streamgages, the Nash-Sutcliffe coefficient for mean monthly streamflow was less than 0.5 (table 14); at those sites streamflow tended to be underestimated during most months.

Similar to the monthly means, simulations of monthly mean base flows (graph C in figs. A2–A12) are considered acceptable (Nash-Sutcliffe coefficients 0.54 to 0.87) except at the gaging station Buffalo Run Lower (Nash-Sutcliffe coefficient 0.38). The magnitude of simulated base-flow fluctuations is less than was observed at many of the streamgages during water years 2000–02, yet the timing of the highs and lows is correct (observations 1 through 36 on graph C in figs. A2–A12). For 2003–06, both the timing and magnitude of the simulated and observed streamflow is predictive and consistent with monthly mean streamflows.

Groundwater Levels

Transient groundwater levels, a lesser objective of calibration, were not well simulated as shown graphically and by Nash-Sutcliffe coefficients of less than zero at most of the 16 wells (figs. A13 and A14). The timing and magnitude of simulated groundwater-level fluctuations can only be considered acceptable for three wells used for calibration—CE 686, Centre Hall, and CE 692. At some wells, the magnitude of the simulated fluctuation was reasonable, but the starting elevation was too high or low (CE 691 and CE 697); at some wells the simulated elevation was reasonable, but the fluctuations were not adequately simulated (Nittany, CE 693, and CE 695); and at some wells, neither the simulated fluctuations nor elevation were acceptable (CE 698, Pine Grove 2).

The poor fit of the model to observed groundwater levels relative to the fit of the model to observed streamflows was not unexpected because the zone-based parameterization of the GSFLOW model is best suited for predictions that integrate large areas of the model domain (such as flux targets), whereas water-level targets are more local. Therefore, the structural error associated with the simplified zone-based model makes it difficult to accurately simulate of groundwater levels in the complex geologic setting of the study area.

Table 14. Nash-Sutcliffe coefficients of model efficiency for streamflow calibration targets in the Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania, water years 2000–06.

[--, not available]

Streamgage site	Calibration target and Nash-Sutcliff coefficient				
	Natural log of daily streamflow	Annual mean streamflow	Monthly mean streamflow	Monthly mean base flow	Mean monthly streamflow
Spring Creek near Axemann, PA	0.65	0.93	0.92	0.87	0.84
Buffalo Run Lower	0.47	0.41	0.48	0.28	0.38
Cedar Run Lower	0.61	0.65	0.75	0.75	0.55
Spring Creek at Houserville, PA	0.58	0.90	0.91	0.82	0.83
Logan Branch Lower	0.58	--	0.78	0.74	0.54
Logan Branch Upper	0.52	0.71	0.75	0.64	0.73
Spring Creek at Milesburg	0.70	0.91	0.90	0.86	0.79
Spring Creek Upper	0.53	0.72	0.75	0.54	0.23
Spruce Creek at Graysville, PA	0.73	0.89	0.82	0.85	-0.16
Slab Cabin Run Lower	0.55	0.81	0.83	0.80	0.71
Slab Cabin Run Upper	0.50	0.96	0.84	0.74	0.35

Water Budget and Groundwater Recharge

The principal objectives of this project were to simulate the water budget and estimate the distribution of groundwater recharge for the study basin for water years 2000–06 by the use of GSFLOW. GSFLOW provides two output files that can be used to view water budgets for the major components of the hydrologic cycle. An example of the annual water budgets compiled from the main GSFLOW output file (gsflow_FINALBUDGET.out) is presented in table 15. Values of other water-budget terms are provided in the GSFLOW Comma-Separated Values (CSV) output file (gsflow.csv). These output files are available from the GSFLOW model archive, available upon request from the USGS Pennsylvania Water Science Center.

Basin Water Budget

Water budgets simulated by GSFLOW for water years 2000–06 are summarized in table 15 as volumes of inflow, outflow, and storage change for each water year and for the entire period. The largest source and sink terms are represented by precipitation and evapotranspiration, respectively. For water years 2000–06, precipitation was more than 99 percent of all inflow; evapotranspiration and streamflow together accounted for 98 percent of all outflow. Withdrawals by wells and quarries represented about 2 percent of the outflow. For water years 2000–06, total inflows of water exceeded total outflows by about 1.7 billion cubic feet (0.47 inches per year over the basin area), so the simulated total storage of water in the basin increased by an amount about equal to the surplus inflow. Contributions from precipitation, streamflow gains, inter-basin groundwater exchanges such as those from the northeast and southwest portions of the study basin, and well withdrawals/injection exceeded those outflows from evapotranspiration, streamflow losses, inter-basin losses, and well withdrawals/injection.

The major terms of the water budget simulated by GSFLOW are shown for water years 2000–06 in figure 24. Water year 2001 was the driest year during the study period and 2004 was the wettest year in terms of both simulated annual precipitation and streamflow (table 15 and fig. 24). Annual outflow as evaporation was relatively constant, however, averaging about 14 billion cubic feet per year, indicating that water is generally available to satisfy the environmental demand for evapotranspiration as simulated by the model. The volume of water in storage increased most in water year 2003, which was a wet year preceded by a dry year, and decreased most during water year 2005, which was a dry year preceded by a wet year.

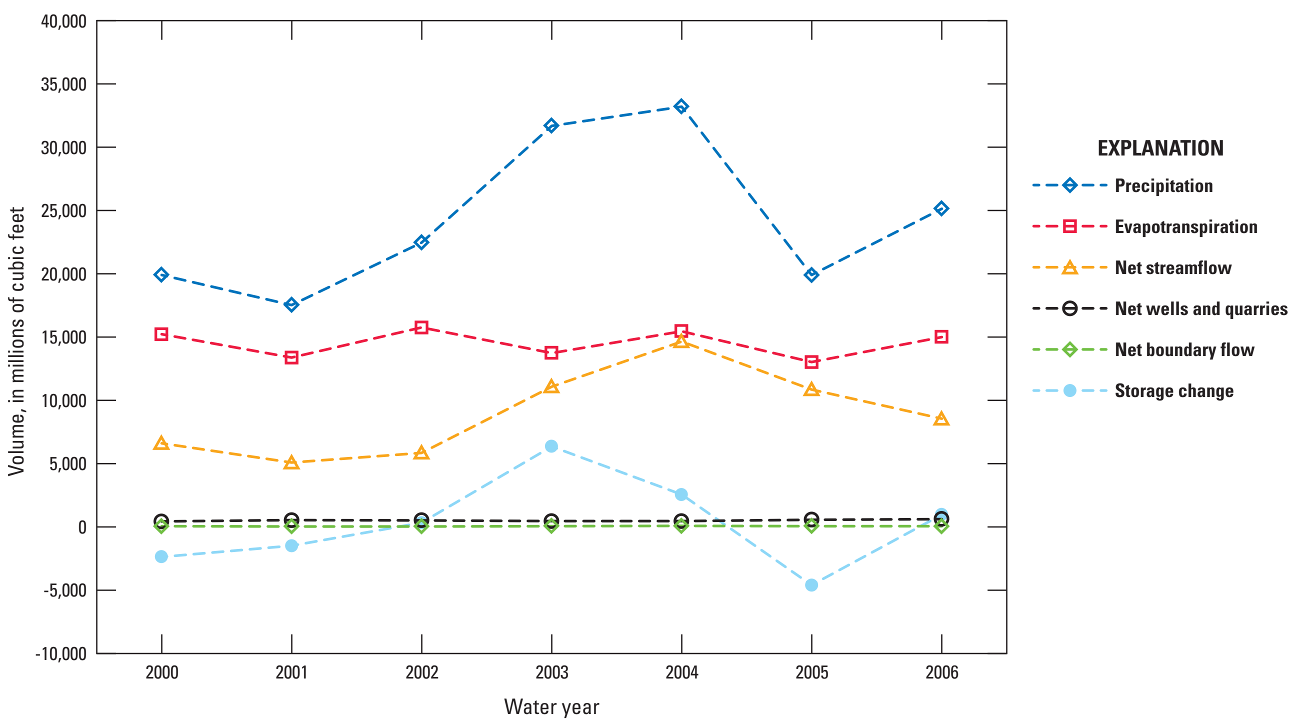


Figure 24. Summary of annual water-budget terms from the GSFLOW simulation, Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, water years 2000–06.

Table 15. Annual water budgets from the GSFLOW simulation for Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania, water years 2000–06.

[Values in the table were computed as differences between volumetric budgets for the last day of each water year given in the GSLFOW main output file (gsflow_FINALBUDGET.out) and converted from cubic meters to cubic feet. All values are reported as thousands of cubic feet except percent discrepancy is dimensionless.]

Water budget term	Water year							Totals for 2000–06
	2000	2001	2002	2003	2004	2005	2006	
Inflows								
Precipitation	19,917,491	17,533,749	22,467,212	31,698,475	33,213,475	19,903,365	25,151,129	169,884,896
Streamflow	41,070	19,216	31,250	115,393	124,025	175,161	247,803	753,919
Groundwater boundary flow	20,790	21,656	22,386	15,993	13,386	14,748	19,645	128,604
Wells	136	117	125	188	213	129	98	1,005
Outflows								
Evapotranspiration	15,224,167	13,380,740	15,750,356	13,744,481	15,464,307	13,027,593	15,001,685	101,593,329
Streamflow	6,654,702	5,093,792	5,883,429	11,198,291	14,782,733	11,039,375	8,786,297	63,438,621
Groundwater boundary flow	61,196	57,945	55,033	73,984	86,556	75,785	60,000	470,500
Wells and quarries	419,892	532,440	509,097	448,497	444,824	563,269	610,238	3,528,256
Inflow minus outflow[1]	-2,379,575	-1,492,823	327,544	6,360,354	2,574,442	-4,612,488	957,947	1,735,400
Storage change[2]								
Land surface	-10,939	96	91	11,626	-602	1,283	266	1,821
Soil zone	-1,234,955	482,469	549,638	1,167,398	48,381	-2,373,430	1,219,417	-141,082
Unsaturated zone	-42,484	-195,043	362,611	1,741,862	-242,683	-1,606,959	177,103	194,407
Saturated zone	-1,086,109	-1,777,948	-589,402	3,438,840	2,741,092	-623,375	-432,888	1,670,209
Total	-2,374,490	-1,490,422	322,918	6,359,577	2,546,543	-4,602,671	963,879	1,725,335
Overall budget error[3]	-5,071	-2,403	4,620	516	28,062	-9,716	-5,967	10,041
Percent discrepancy	-0.03	-0.01	0.02	0.00	0.08	-0.05	-0.02	0.01

[1]The "Inflow minus outflow" budget term does not exactly equal the difference between inflow and outflows shown in this table because of rounding in the GSFLOW output file.

[2]Minus is loss of water from storage.

[3]Inflows - outflows - change in storage.

Simulated daily fluxes for the major budget terms (precipitation, evapotranspiration, and streamflow) from the GSFLOW Comma Separated Value (CSV) output file are shown in figure 25. The regular seasonal variability of evapotranspiration is apparent—high rates of water loss in the summer and low rates of loss in the winter. Simulated streamflow was low many days during water years 2000 and 2001, as well as during the summer months of water years 2005 and 2006.

An estimate of annual groundwater recharge from GSFLOW was summarized in table 16 from simulated values of daily flux of water from the unsaturated zone to the saturated zone (uzf_recharge). Recharge from the unsaturated zone, expressed as a depth over the study area, ranged from 5.4 inches in 2001 (the driest year) to 22 inches in 2004 (the wettest year) and averaged about 12.4 inches. The GSFLOW model average for water years 2000–06 is less than the estimate of 15.2 inches of groundwater recharge derived from base-flow separation of the streamflow hydrograph. Recharge, expressed as a percentage of precipitation, ranged from 16 percent in water years 2001 and 2002 to 42 percent in water year 2005. The large amount of recharge relative to precipitation in water year 2005 was caused by infiltration of precipitation during previous wet years that did not reach the saturated zone until water year 2005.

Variability in the simulated daily flux of recharge from the unsaturated zone to the saturated zone (uzf_recharge) is

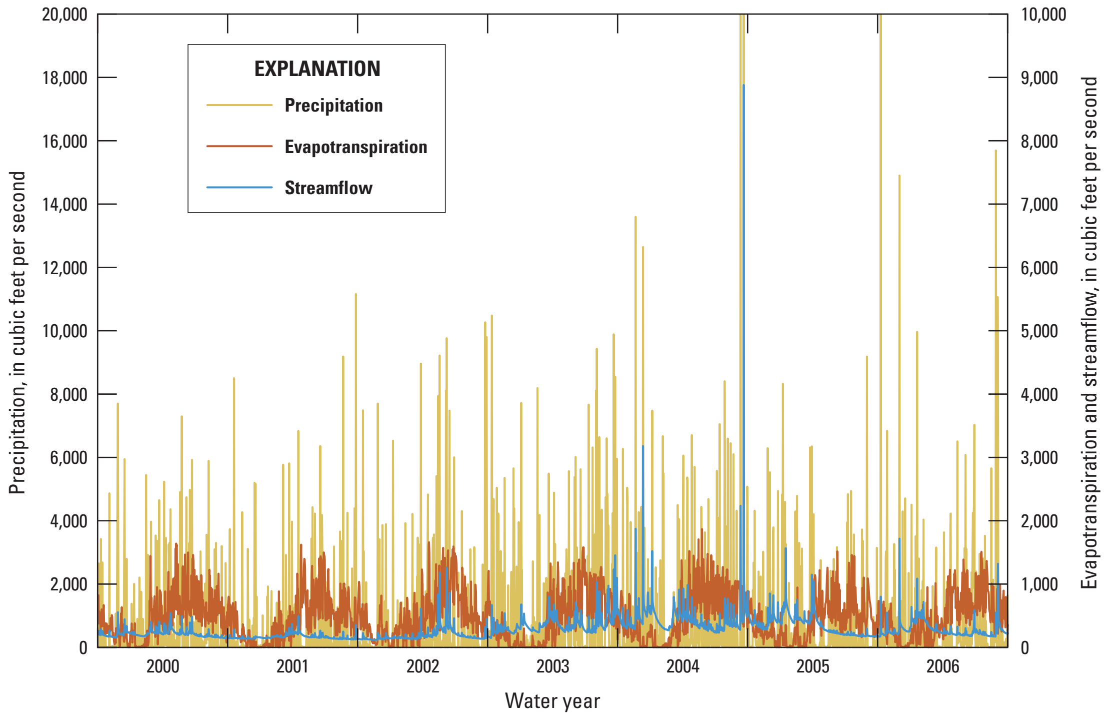


Figure 25. Daily fluxes of precipitation (basinppt), evapotranspiration (basinactet), and streamflow (basinstrmflow) from the GSFLOW Comma Separated Value (CSV) output file.

Table 16. Simulated flux of recharge from the unsaturated zone to the saturated zone (uzf_recharge) derived from the GSFLOW Comma Separated Value (CSV) output file.

Mean recharge rate from unsaturated to saturated zone (uzf_recharge)	Water year						
	2000	2001	2002	2003	2004	2005	2006
In cubic feet per second	132	91	112	308	370	265	182
As inches per year	7.8	5.4	6.6	18.3	22.0	15.8	10.8
As percent of precipitation	21	16	16	31	35	42	23

shown in figure 26. The amount of recharge varied seasonally in water years 2000, 2001, 2005 and 2006—recharge was greater in the winter and spring than in the summer and fall. However, in water years 2002–04 substantial amounts of water recharged the saturated zone regardless of season.

The recharge from the unsaturated zone to the saturated zone (uzf_recharge) is compared to basin streamflow in figure 27. Recharge was much less than the base streamflow for dry periods in water years 2000–02 and 2005–06; during those times the streamflow was being sustained by depletion of groundwater storage. This comparison illustrates why base flows determined by the use of hydrograph-separation methods are not usually a good approximation of groundwater recharge at time scales of less than one year.

Groundwater Recharge

The distribution of net recharge derived from GSFLOW across the basin is illustrated for the driest water year of the study period (2001) in figure 28 and the wettest water year (2004) in figure 29. Areas in the basin where rates of groundwater recharge are much higher than average, especially during wet years, might be considered critical for maintaining the flow of springs, stream base flow, or the source of water to supply wells.

Net recharge derived from GSFLOW differs from the infiltration flux from PRMS in that net recharge from GSFLOW is the net difference in the exchange of water between the saturated zone and land surface by MODFLOW-NWT grid cell, whereas infiltration from PRMS is a downward vertical flux that originates at the land surface summarized by HUC. Thus, the resulting GSFLOW net recharge distributions for 2001 and 2004 in figures 28 and 29 differ from the PRMS-only infiltration (fig. 9) and are attributed to a more complete accounting of water in the GSFLOW model. The net recharge is useful for assessing the areal distribution of locations where recharge exceeds groundwater discharge. The sum of net recharge for all cells does not equal total recharge for the basin because of the large negative net recharge values computed for model cells having gaining streams and surface leakage. Net recharge rate for each cell is computed as

Net recharge = (*Recharge* – *Groundwater ET* – *Surface leakage* – *Stream seepage*),

where

Recharge is water added to the saturated zone from the UZF package,

Groundwater ET is evapotranspiration from the saturated zone,

Surface leakage is groundwater discharge to the land surface where the water table intercepts the land surface, and

Stream seepage at model cells with streams, is groundwater discharge to stream or streamflow loss to groundwater.

The maps of the simulated distribution and magnitude of annual net recharge differ for water years 2001 (fig. 28) and 2004 (fig. 29). In the dry water year 2001, the net recharge for most model cells was 0 to 1,000 cubic feet per day (red and orange cells). Net recharge was greater than 1,500 cubic feet per day (green, blue, and purple cells) in a few model cells in valleys along losing streams. Net recharge was less than zero (white cells) in areas where water from the saturated zone was discharging to land surface on mountains and along gaining streams. In the wet water year 2004, except for the mountain areas, net recharge in model cells mostly ranged from 1,500 to 5,000 cubic feet per day (green and blue cells) and was even greater (purple cells) in a few valleys along losing streams (fig. 29).

The differences between the wet and dry water years are highlighted in figure 30, which shows the simulated net recharge for water year 2004 minus net recharge for water year 2001. The difference was positive in most parts of the basin, indicating that net recharge was greater in 2004 than in 2001. Areas with the greatest increase in recharge include model cells in the Scotia Barrens and valley floor between there and Bellefonte, along the toe slopes of Tussey and Bald Eagle Mountains, and some cells along Nittany Mountain. The Scotia Barrens, located west of State College, are approximately 200 ft higher than the Nittany Valley floor. The ridge is underlain by the Gatesburg Formation, which is characterized by a coarse-grained dolomite, interbedded orthoquartzite and sandy dolomite (Fulton and others, 2005). The substantially greater net recharge in that area for 2004 compared to 2001 is a function of the thick unsaturated zone, large specific yield, and large hydraulic conductivity associated with the Gatesburg Formation.

The difference between net recharge in 2004 and 2001 was negative in a few areas on the mountains and along streams (orange and red cells). Simulated net recharge was greater during 2001 than during 2004 in a few parts of Tussey, Nittany, and Bald Eagle Mountains because the water table rose during the wet year 2004, causing discharge of water from the saturated zone to land surface to increase, which reduced net recharge. Net recharge was also less in 2004 than in 2001 in model cells along some streams because substantially greater amounts of water discharged along stream valleys during the wet year 2004 than during the dry year 2001.

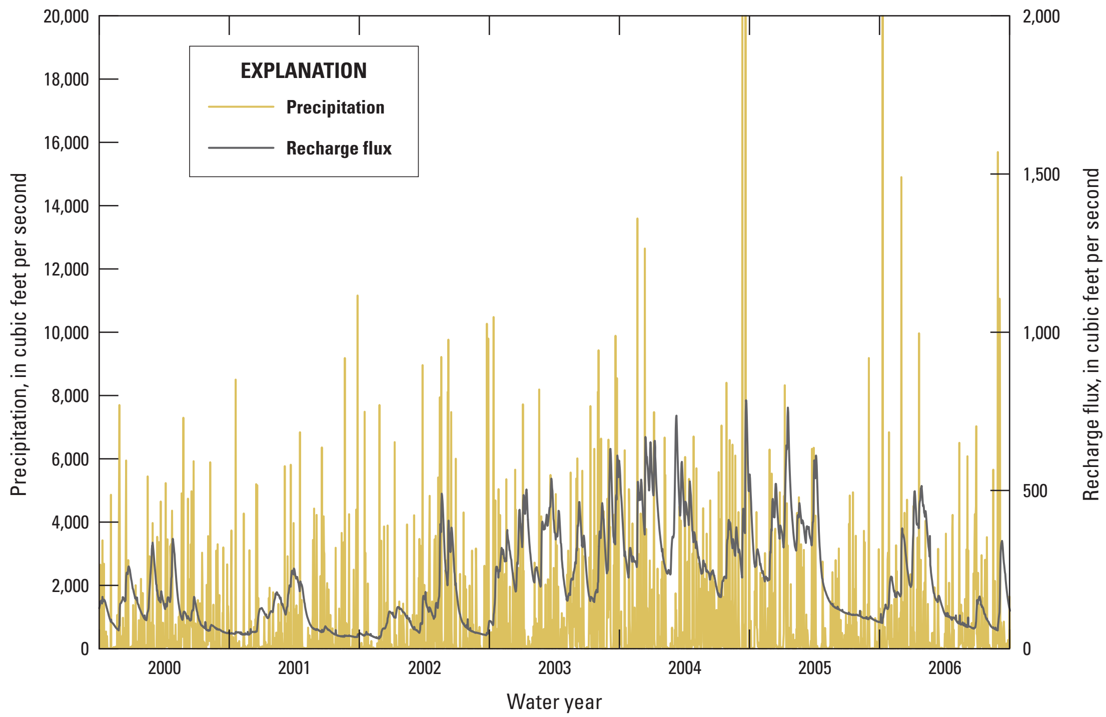


Figure 26. Daily fluxes of precipitation (basinppt) and recharge from the unsaturated zone to the saturated zone (uzf_recharge) from the GSFLOW Comma Separated Value (CSV) output file.

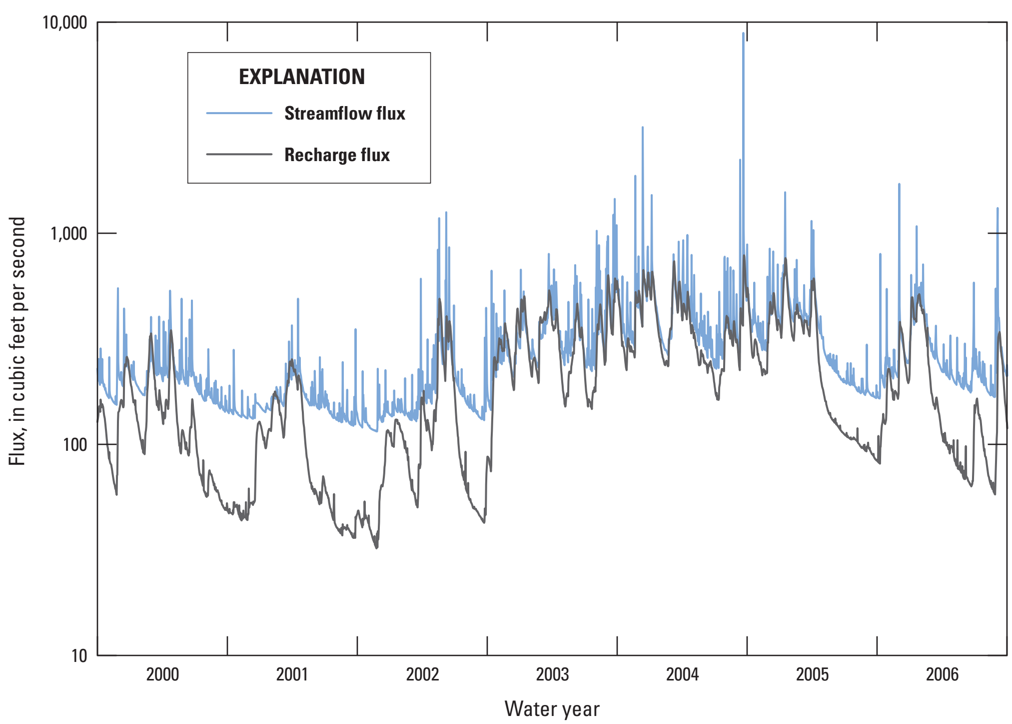
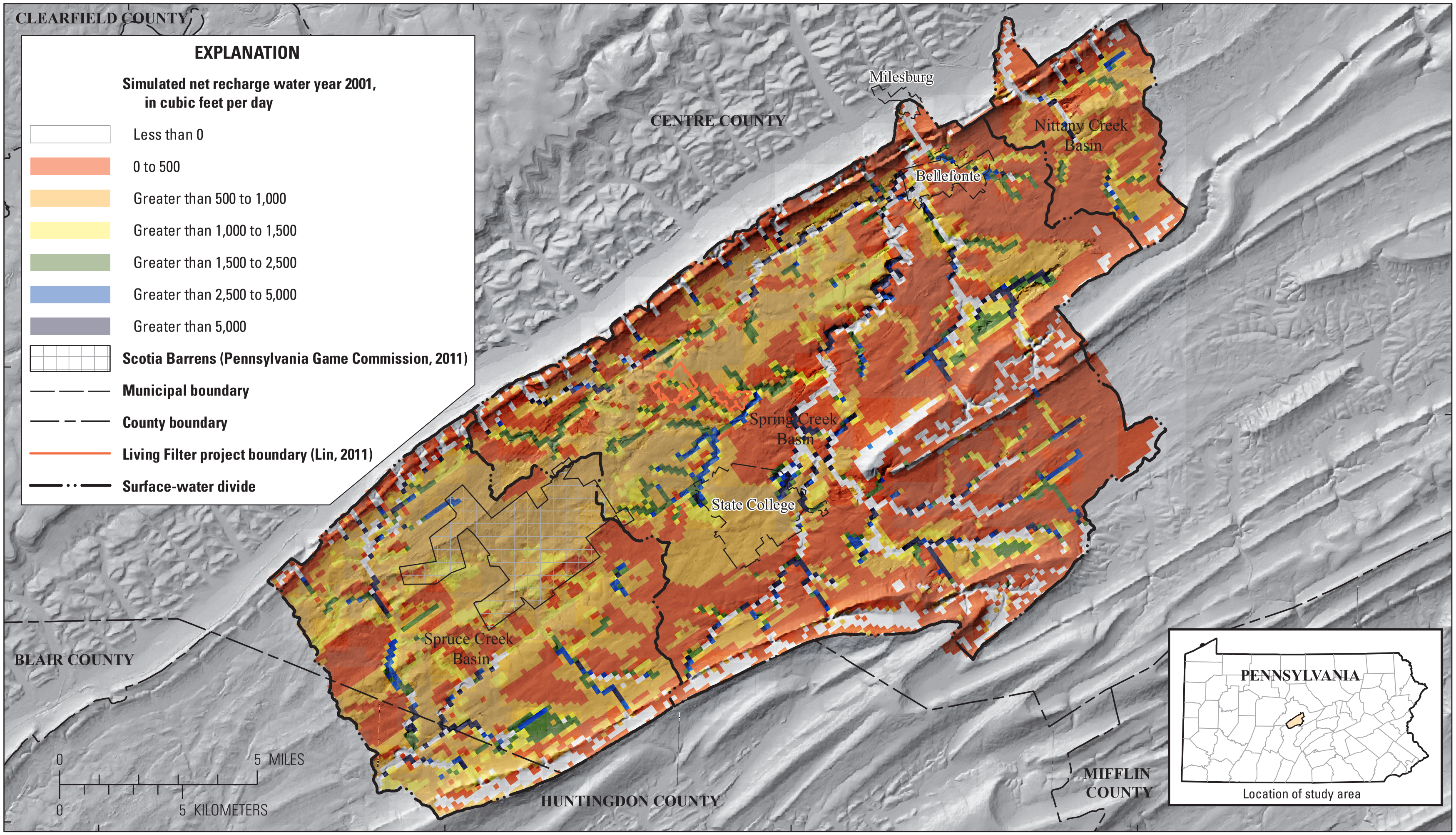


Figure 27. Daily fluxes of streamflow (basinstrmflow) and recharge from the unsaturated zone to the saturated zone (uzf_recharge) derived from the GSFLOW Comma Separated Value (CSV) output file.



Base from U.S. Geological Survey digital data, 1972
Universal Transverse Mercator projection, Zone 18, NAD 1983
Shaded relief from PAMAP Program, 2008

Figure 28. Net recharge simulated by GSFLOW in Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania, water year 2001.

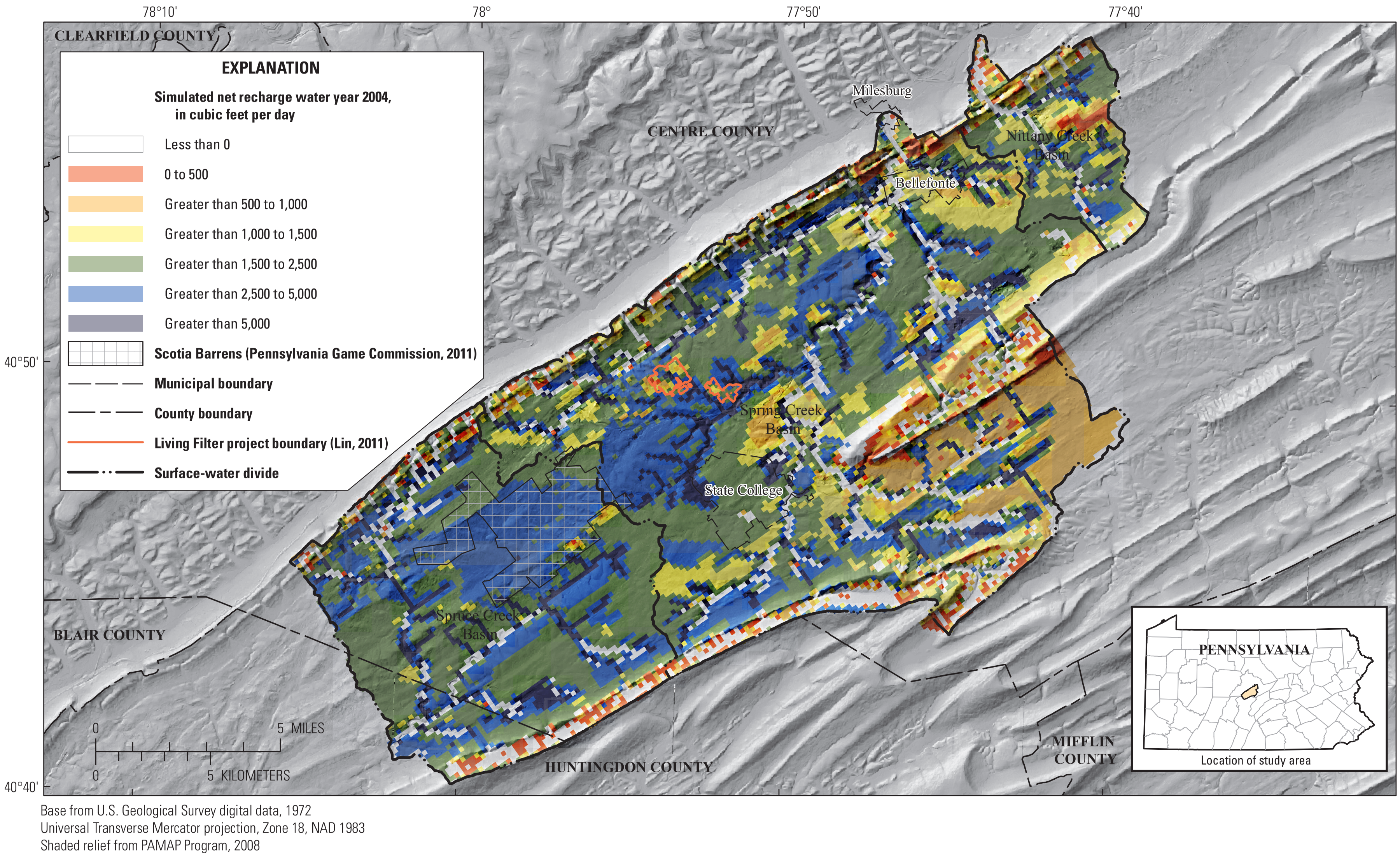
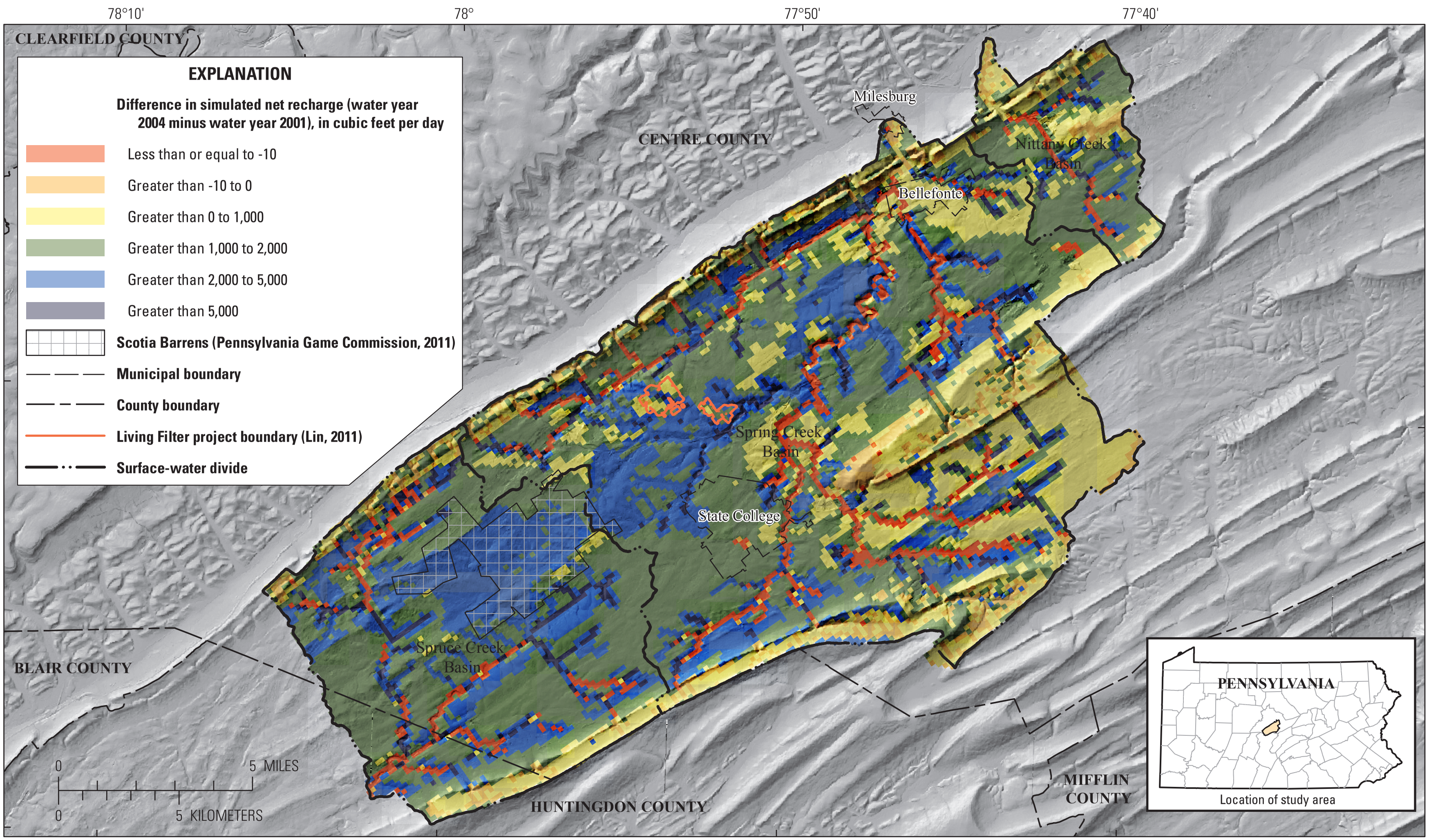


Figure 29. Net recharge simulated by GSFLOW in Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania, water year 2004.



Base from U.S. Geological Survey digital data, 1972
Universal Transverse Mercator projection, Zone 18, NAD 1983
Shaded relief from PAMAP Program, 2008

Figure 30. Difference in net recharge between water years (2004 minus 2001) simulated by GSFLOW in Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania.

Model Limitations

The hydrologic model of the Spring Creek and Nittany Creek Basins, and parts of the Spruce Creek Basin was developed to simulate a basin-scale water budget and groundwater recharge for water years 2000–06. The model is probably adequate for simulating the regional water budget; however, substantial errors between simulated and observed groundwater levels suggest that use of the maps of groundwater recharge should be limited to providing general information about the overall pattern and magnitude of spatial variability in recharge.

The GSFLOW model developed for the basin is limited by the availability and reliability of data used for its construction and calibration, but the principal limitations are probably the result of model simplifications and spatial resolution. Development of a numerical model requires simplification of the regional groundwater/surface-water system; however, for this study basin in karst terrain, simplification of the extreme heterogeneity with respect to hydraulic conductivity may not allow accurate representation of groundwater levels and flows, especially at the local scale. Thus, simulated results from GSFLOW at the local scale may not compare closely to observed fluxes or levels. Comparisons of simulated and observed daily streamflows and groundwater levels show the degree to which the GSFLOW model was able to match local observations. Some locations are well characterized by the GSFLOW model; in other areas, the GSFLOW model is a poor representation of the natural system. Although the model provides a reasonable assessment of the basin water budget and streamflow hydrographs for the period 2000–06, caution should be used when examining model results at specific locations.

The spatial resolution that could be simulated in the GSFLOW model was limited by the horizontal and vertical model discretization. The topographically and hydrogeologically delineated HRUs, with stream buffers based on a width of 1,312 feet (400 meters), may have introduced surface-water/groundwater interaction zones that are not based on the true riparian areas for each stream segment and do not include the full extent of the riparian areas of stream segments. In addition, the resolution of the MODFLOW-NWT cells, 656 by 656 feet (200 by 200 meters) in horizontal dimension, allowed only a coarse representation of the interaction between groundwater and streams because the groundwater head at the stream was averaged over the large area of the cell, and because the physical stream-segment properties may not have been accurately represented. The timing of streamflow routing between stream segments might have been improved by using a kinematic wave method in the SFR2 package. However, because the model uses a daily time step, use of advanced streamflow routing methods was determined to be unnecessary. The thick vertical layers in the model of 300 feet were used to help mitigate computational difficulties caused by the steep relief on the mountains, affecting the ability to accurately simulate shallow groundwater levels, especially in areas where vertical gradients are greatest, such as beneath the mountains and streams.

The hydrologic model could be used to compare simulations of historic conditions of climate or land use during water years 2000–06 to simulations with alternative values for those conditions. Evaluation of differences between the simulations could be used to help understand the effects of those alternative conditions on the water budget and groundwater recharge. As a planning tool, the model could be used to simulate the effects of future hypothetical changes at the basin scale.

Summary and Conclusions

Rapid growth and development in the study basin (Spring Creek and Nittany Creek Basins and the headwaters of Spruce Creek Basin) has resulted in land-use changes and increased water use, influencing (1) the quantity and availability of runoff and groundwater, (2) surface-water/groundwater interactions, and (3) aquatic resources in the study basin. Because of the hydrologic connectivity between surface-water and groundwater in parts of the basins, a hydrologic model that accounts for groundwater and surface-water components (GSFLOW model) was constructed to simulate the interactions between both systems.

ClearWater Conservancy and the Pennsylvania Department of Environmental Protection identified a number of priorities for the project, two of which were to (1) create a coupled-regional model to compute the water budget for the study basin using GSFLOW for water years 2000–06 and (2) identify areas of greater than average recharge, which can be used by decision makers in managing water resources in the study basin.

The cumulative and annual water budgets for water years 2000–06 for each of the storage reservoirs were simulated by GSFLOW. The largest source and sink terms are represented by precipitation and evapotranspiration, respectively. For water years 2002–06, a net surplus in the water budget of about 1.7 billion cubic feet was computed, where the inflows (precipitation, streamflow gains, inter-basin groundwater exchanges, well withdrawals/injection) exceeded outflows (evapotranspiration, streamflow losses, inter-basin losses, and well withdrawals/injection). The surplus inflow was balanced in the budget by an increase in storage by about the same amount. Groundwater withdrawals accounted for about 2 percent of the simulated outflow.

Simulated values of streamflow and groundwater levels from GSFLOW were compared to observations from 11 streamgages and 16 wells for water years 2000–06 during model calibration. Simulations of daily streamflow are considered acceptable for most streamgages except at the station Buffalo Run Lower. During wet years of high streamflow, the model slightly overestimated annual streamflow at most streamgages, and during dry years streamflow generally was slightly underestimated. The timing and magnitude of the simulated monthly mean streamflow corresponds closely to the observed streamflow. Simulations of mean monthly flow do not match the observations as closely as the daily and monthly mean streamflow calibration targets; at many of the streamgages, mean monthly flow was underestimated in March and April.

Transient groundwater levels, a lesser objective of calibration, were not adequately simulated at most observation wells. The timing and magnitude of the simulated groundwater-level fluctuations can only be considered acceptable for three wells used for calibration—CE 686, Centre Hall, and CE 692. The poor fit of the model to observed groundwater levels relative to the fit of the model to observed streamflows was not unexpected because the zone-based parameterization of the GSFLOW model is best suited for predictions that integrate large areas of the model domain (such as flux targets), whereas water-level targets are more local.

Differences in the magnitude and distribution of simulated net recharge between wet and dry periods were evaluated by comparing net recharge from water year 2001 (driest) to water year 2004 (wettest). Areas in the basin where rates of groundwater recharge are much higher than average and are capable of accepting substantially greater quantities of recharge during wet years might be considered critical for maintaining the flow of springs, stream base flow, or the source of water to supply wells. Areas where simulated rates of net recharge increased the most between the driest water year (2001) and wettest water year (2004) include the Scotia Barrens and valley floor between there and Bellefonte, along the toe slopes of Tussey and Bald Eagle Mountains, and some cells along Nittany Mountain.

The model is judged adequate for simulating the regional water budget; however, substantial errors between simulated and observed groundwater levels suggest that use of the maps of groundwater recharge should be limited to providing general information about the overall pattern and magnitude of spatial variability in recharge. The model could be used to compare simulations of historic conditions of climate or land use to alternative values for those conditions to help understand the effects of those alternative conditions on the water budget and groundwater recharge. As a planning tool, the model could be used to simulate the effects of future hypothetical changes at the basin scale.

An archive of the hydrologic model (including all GSFLOW files) is stored in the U.S. Geological Survey Pennsylvania Water Science Center digital model repository. The files are available upon request.

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Tables 1 and 7

Table 1. Precipitation Runoff Modeling System parameter values assigned to hydrologic response units for Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania.

[PRMS, Precipitation Runoff Modeling System; HRU, hydrologic response unit; gm/cm^3, grams per cubic centimeter; id, identifier; precip, precipitation; GWR, groundwater reservoir; elev, elevation in feet above the North American Vertical Datum of 1988; temp, temperature; precip, precipitation; mm, millimeters; cfs, cubic feet per second; cms, cubic meters per second]

PRMS parameter name	Module	Description of model parameter	Units	Minimum value	Maximum value	Mean value
adj_by_hru	climate_hru	Flag to indicate whether to adjust precipitation and air temperature by HRU or subbasin (0=subbasin; 1=HRU)	None	0	0	0
adjmix_rain	climateflow	Monthly (January to December) factor to adjust rain proportion in a mixed rain/snow event	Decimal fraction	0.6	1.4	1.06436
albset_rna	snowcomp	Albedo reset—rain, accumulation stage. Fraction of rain in a mixed precipitation event above which the snow albedo is not reset, applied during the snowpack accumulation stage	Decimal fraction	0.8	0.8	0.8
albset_rnm	snowcomp	Albedo reset—rain, melt stage. Fraction of rain in a mixed precipitation event above which the snow albedo is not reset, applied during the snowpack melt stage	Decimal fraction	0.6	0.6	0.6
albset_sna	snowcomp	Albedo reset—snow, accumulation stage. Minimum snowfall, in water equivalent, needed to reset snow albedo during the snowpack accumulation stage	Inches	0.05	0.05	0.05
albset_snm	snowcomp	Albedo reset—snow, melt stage. Minimum snowfall, in water equivalent, needed to reset snow albedo during the snowpack melt stage	Inches	0.2	0.2	0.2
basin_area	basin	Area of basin	Acres	146,350	146,350	146,350
basin_tsta	climateflow	Index of temperature station used to compute basin temperature values	None	0	0	0
carea_max	climateflow	Maximum possible area contributing to surface runoff expressed as a portion of the HRU area	Decimal fraction	0.25	0.25	0.25
cascade_flg	cascade	Flag to indicate cascade type (0=allow many to many; 1=force one to one)	None	0	0	0
cascade_tol	cascade	Cascade area below which a cascade link is ignored	Acres	0.5	0.5	0.5
cecn_coef	snowcomp	Monthly (January to December) convection condensation energy coefficient	Calories per degree Celsius above 0	13.04718	13.04718	13.04718
circle_switch	cascade	Switch to check for circles (0=no check; 1=check)	None	0	0	0
cov_type	intcp_dev	Vegetation cover type for each HRU (0=bare soil, 1=grasses, 2=shrubs, 3=trees)	None	0	4	1.87093
covden_sum	intcp_dev	Summer vegetation cover density for the major vegetation type on each HRU	Decimal fraction	0.14671	1	0.57692
covden_win	intcp_dev	Winter vegetation cover density for the major vegetation type on each HRU	Decimal fraction	0.03631	0.76499	0.25523
den_init	snowcomp	Initial density of new-fallen snow	gm/cm^3	0.1	0.1	0.1

Table 1. Precipitation Runoff Modeling System parameter values assigned to hydrologic response units for Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania.—Continued

[PRMS, Precipitation Runoff Modeling System; HRU, hydrologic response unit; gm/cm^3, grams per cubic centimeter; id, identifier; precip, precipitation; GWR, groundwater reservoir; elev, elevation in feet above the North American Vertical Datum of 1988; temp, temperature; precip, precipitation; mm, millimeters; cfs, cubic feet per second; cms, cubic meters per second]

PRMS parameter name	Module	Description of model parameter	Units	Minimum value	Maximum value	Mean value
den_max	snowcomp	Average maximum snowpack density	gm/cm^3	0.6	0.6	0.6
elev_units	basin	Flag to indicate the units of the elevation values (0=feet, 1=meters)	None	0	0	0
emis_noppt	snowcomp	Average emissivity of air on days without precipitation	Decimal fraction	0.76024	0.76024	0.76024
epan_coef	intcp_dev	Monthly (January to December) evaporation pan coefficient	None	1	1	1
fall_frost	transp_frost	The solar date (number of days after winter solstice) of the first killing frost of the fall	Solar date	299	315	307.80941
fastcoef_lin	soilzone	Linear coefficient in equation to route preferential-flow storage downslope for each HRU	1/day	0.0004	0.24519	0.01073
fastcoef_sq	soilzone	Non-linear coefficient in equation used to route preferential-flow storage down slope for each HRU	None	0.02	0.02	0.02
freeh2o_cap	snowcomp	Free-water holding capacity of snowpack expressed as a decimal fraction of the frozen water content of the snowpack (pk_ice)	Decimal fraction	0.15314	0.15314	0.15314
gvr_cell_id	gsflow_prms2mf	Finite-difference cell associated with a gravity reservoir	None	411	22,364	9,514.81453
gvr_cell_pct	gsflow_prms2mf	Decimal fraction of HRU area associated with a finite-difference cell	None	0	1.00195	0.49626
gvr_hru_id	gsflow_prms2mf	HRU associated with a gravity reservoir	None	1	829	423.48547
gvr_hru_pct	gsflow_prms2mf	Decimal fraction of HRU area associated with a gravity reservoir	None	0	0.39636	0.02778
hru_area	basin	Area of each HRU	Acres	22.2394	6,081.58	176.54226
hru_aspect	soltab	Aspect of each HRU	Degrees	0	315	166.26659
hru_deplcrv	snowcomp	Index number for the snowpack areal depletion curve associated with each HRU	None	1	1	1
hru_down_id	cascade	Index number of the downslope HRU to which the upslope HRU contributes flow	None	0	829	245.22263
hru_elev	basin	Mean elevation for each HRU	Elev_units	208.00001	688.00002	378.49097
hru_frac_apply[1]	intcp_dev	Portion of HRU that an application rate is applied	Decimal fraction	0.00349	0.69496	0.28876
hru_lat	soltab	Latitude of each HRU	Degrees	40.67987	40.9718	40.81942
hru_pct_up	cascade	Fraction of HRU area used to compute flow contributed to a down slope HRU or stream segment for cascade area.	decimal fraction	0	1	0.60406
hru_percent_imperv	basin	Fraction of each HRU area that is impervious	Decimal fraction	0	0.19126	0.0015
hru_slope	soltab	Slope of each HRU, specified as change in vertical length divided by change in horizontal length	Decimal fraction	0.01711	0.42313	0.1137
hru_strmseg_down_id	cascade	Index number of the stream segment that cascade area contributes flow	None	0	387	69.74818

Table 1. Precipitation Runoff Modeling System parameter values assigned to hydrologic response units for Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania.—Continued

[PRMS, Precipitation Runoff Modeling System; HRU, hydrologic response unit; gm/cm^3, grams per cubic centimeter; id, identifier; precip, precipitation; GWR, groundwater reservoir; elev, elevation in feet above the North American Vertical Datum of 1988; temp, temperature; precip, precipitation; mm, millimeters; cfs, cubic feet per second; cms, cubic meters per second]

PRMS parameter name	Module	Description of model parameter	Units	Minimum value	Maximum value	Mean value
hru_subbasin	climate_hru	Index of subbasin assigned to each HRU	None	1	14	5.56333
hru_type	basin	Type of each HRU (0=inactive; 1=land, 2=lake, 3=swale)	None	1	3	1.17612
hru_up_id	cascade	Index of HRU containing cascade area	None	1	829	405.65985
id_obsrunoff	gsflow_sum	Identifier for streamflow-gaging station at outlet		4	4	4
imperv_stor_max	climateflow	Maximum impervious area retention storage for each HRU	Inches	0.00321	0.07934	0.02132
irr_type[1]	intcp_dev	Method of application of water for each application time series (0=sprinkler (intercep applies), 1=furrow/drip (no intercept), 2=ignore)	None	1	1	1
melt_force	snowcomp	Julian date to force snowpack to spring snowmelt stage; varies with region depending on length of time that permanent snowpack exists	Julian day	120	120	120
melt_look	snowcomp	Julian date to start looking for spring snowmelt stage. Varies with region depending on length of time that permanent snowpack exists	Julian day	45	45	45
mnsziter	gsflow_prms	Version identifiers associated with the Parameter File	String	25	25	25
mxsziter	hru_sum	Switch for HRU monthly and yearly summary (0=off, 1=on)	None	75	75	75
napp_to_hru[1]	intcp_dev	HRU id to apply an observed application rate	None	256	366	328.33333
potet_sublim	intcp_dev	Fraction of potential ET that is sublimated from the snow surface	Decimal fraction	0.18293	0.18293	0.18293
ppt_rad_adj	climateflow	Monthly minimum precipitation, if basin precipitation exceeds this value, radiation is mutiplied by radj_sppt or radj_wppt adjustment factor	Inches	0.02	0.02	0.02
precip_units	climateflow	Units for measured precipitation (0=inches; 1=mm)	None	0	0	0
pref_flow_den	soilzone	Preferential-flow pore density for each HRU	Decimal fraction	0.00247	0.05826	0.01574
rad_trncf	snowcomp	Transmission coefficient for short-wave radiation through the winter vegetation canopy	Decimal fraction	0.1659	0.68029	0.52575
radj_sppt	climateflow	Adjustment factor for computed solar radiation for summer day with greater than ppt_rad_adj inches precip	Decimal fraction	0.44	0.44	0.44
radj_wppt	climateflow	Adjustment factor for computed solar radiation for winter day with greater than ppt_rad_adj inches precip	Decimal fraction	0.5	0.5	0.5
radmax	climateflow	Maximum fraction of the potential solar radiation that may reach the ground due to haze, dust, smog	Decimal fraction	0.8	0.8	0.8
rain_sub_adj	climate_hru	Monthly (January to December) adjustment factor to measured precipitation determined to be rain for each subbasin	Decimal fraction	0.8	1.2	1.05711
runoff_units	obs_dev	Measured runoff units (0=cfs; 1=cms)	None	0	0	0

Table 1. Precipitation Runoff Modeling System parameter values assigned to hydrologic response units for Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania.—Continued

[PRMS, Precipitation Runoff Modeling System; HRU, hydrologic response unit; gm/cm^3, grams per cubic centimeter; id, identifier; precip, precipitation; GWR, groundwater reservoir; elev, elevation in feet above the North American Vertical Datum of 1988; temp, temperature; precip, precipitation; mm, millimeters; cfs, cubic feet per second; cms, cubic meters per second]

PRMS parameter name	Module	Description of model parameter	Units	Minimum value	Maximum value	Mean value
sat_threshold	soilzone	Water holding capacity of the gravity and preferential-flow reservoirs; difference between field capacity and total soil saturation for each HRU	Inches	0.99995	14.99963	5.33114
settle_const	snowcomp	Snowpack settlement time constant	Decimal fraction	0.1	0.1	0.1
slowcoef_lin	soilzone	Linear coefficient in equation to route gravity-reservoir storage down slope for each HRU	1.0/day	0.001	0.13949	0.012
slowcoef_sq	soilzone	Non-linear coefficient in equation to route gravity-reservoir storage down slope for each HRU	None	0.015	0.015	0.015
smidx_coef	srunoff_smidx	Coefficient in non-linear contributing area algorithm	Decimal fraction	0.0007	0.02628	0.00491
smidx_exp	srunoff_smidx	Exponent in non-linear contributing area algorithm	1.0/inch	0.3	0.3	0.3
snarea_curve	snowcomp	Snow area depletion curve values, 11 values for each curve (0.0 to 1.0 in 0.1 increments)	Decimal fraction	0.05	1	0.58318
snarea_thresh	snowcomp	Maximum threshold snowpack water equivalent below which the snow-covered-area curve is applied; varies with elevation	Inches	5.77157	48.45613	20.46169
snow_intcp	intcp_dev	Snow interception storage capacity for the major vegetation type in each HRU	Inches	0	0.07155	0.01336
snow_sub_adj	climate_hru	Monthly (January to December) adjustment factor to measured precipitation determined to be snow for each subbasin	Decimal fraction	1	1.2	1.1
snowinfil_max	climateflow	Maximum snow infiltration per day	Inches/day	1.61992	2.76008	2.48885
soil2gw_max	soilzone	Maximum amount of the capillary reservoir excess that is routed directly to the GWR for each HRU	Inches	0	0.5	0.06834
soil_moist_init	soilzone	Initial value of available water in capillary reservoir for each HRU	Inches	1	1	1
soil_moist_max	climateflow	Maximum available water holding capacity of capillary reservoir from land surface to rooting depth of the major vegetation type of each HRU	Inches	2.00003	9.99998	5.88824
soil_rechr_init	soilzone	Initial storage for soil recharge zone (upper part of capillary reservoir where losses occur as both evaporation and transpiration) for each HRU; must be less than or equal to soil_moist_init	Inches	0.1	0.1	0.1
soil_rechr_max	climateflow	Maximum storage for soil recharge zone (upper portion of capillary reservoir where losses occur as both evaporation and transpiration); must be less than or equal to soil_moist	Inches	0.70175	1.46576	1.11072
soil_type	soilzone	Soil type of each HRU (1=sand; 2=loam; 3=clay)	None	2	2	2

Table 1. Precipitation Runoff Modeling System parameter values assigned to hydrologic response units for Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania.—Continued

[PRMS, Precipitation Runoff Modeling System; HRU, hydrologic response unit; gm/cm^3, grams per cubic centimeter; id, identifier; precip, precipitation; GWR, groundwater reservoir; elev, elevation in feet above the North American Vertical Datum of 1988; temp, temperature; precip, precipitation; mm, millimeters; cfs, cubic feet per second; cms, cubic meters per second]

PRMS parameter name	Module	Description of model parameter	Units	Minimum value	Maximum value	Mean value
spring_frost	transp_frost	The solar date (number of days after winter solstice) of the last killing frost of the spring	Solar date	107	119	113.69843
srain_intcp	intcp_dev	Summer rain interception storage capacity for the major vegetation type in each HRU	Inches	0	0.05	0.03138
ssr2gw_exp	soilzone	Non-linear coefficient in equation used to route water from the gravity reservoir to the GWR for each HRU	None	1	1	1
ssr2gw_rate	soilzone	Linear coefficient in equation used to route water from the gravity reservoir to the GWR for each HRU	1/day	0.05	0.73644	0.11593
ssstor_init	soilzone	Initial storage of the gravity and preferential-flow reservoirs for each HRU	Inches	2	2	2
subbasin_down	subbasin	Index number for the downstream subbasin whose inflow is outflow from this subbasin	None	0	14	8.35714
szconverge	gsflow_prms2mf	Convergence criterion for checking soil-zone flows	Inches	0.005	0.005	0.005
temp_units	climateflow	Flag to indicate the units of measured air-temperature values (0=Fahrenheit, 1=Celsius)	None	0	0	0
tmax_allrain	climateflow	Monthly (January to December) maximum air temperature when precipitation is assumed to be rain; if HRU air temperature is greater than or equal to this value, precipitation is rain	Temp_units	39	39	39
tmax_allsnow	climateflow	Monthly (January to December) maximum air temperature when precipitation is assumed to be snow; if HRU air temperature is less than or equal to this value, precipitation is snow	Temp_units	35	35	35
tmax_hru_adj	climateflow	Adjustment to minimum temperature for each HRU, estimated based on slope and aspect	Temp_units	0	0	0
tmin_hru_adj	climateflow	Adjustment to minimum temperature for each HRU, estimated based on slope and aspect	Temp_units	0	0	0
tstorm_mo	snowcomp	Monthly flag (January to December) for prevalent storm type (0=frontal storms, 1=convective storms)	None	0	1	0.5
wrain_intcp	intcp_dev	Winter rain interception storage capacity for the major vegetation type in the HRU	Inches	0	0.03768	0.01798

[1]The parameters irr_type, napp_to_hru, and hru_frac_apply are not included in GSFLOW version 1.1.5 and are used to apply the time series of effluent data to the canopy of the Living Filter on an area-weighted basis to all HRUs affected by the Living Filter. Application of the effluent uses the same computation methods as used for rain on the canopy.

Table 7. Parameters used to represent the hydraulic conductivity of geologic units in the MODFLOW-NWT steady-state model and horizontal hydraulic conductivity values from previous studies for Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania.

[ft/d, feet per day; ft, foot; max, maximum; —, no data]

Geologic period	Formation[1]	Description	Aquifer type	Parameter name used for hydraulic conductivity of the formation, in this study	K Ranks (based on productivity estimates of Parizek and Filley, 1982)	Hydraulic conductivity (K) values from other studies (ft/d)						
						Model values from Curtin Gap study (Gannett Fleming, 2008)	Model values from Brachet (2004)	Reported median aquifer-test values in Fulton and others (2005)	Model values from study in Blair Co (Lindsey, 2004)	K Parizek (assume 500 ft thick)	Model values K(max) from Todd Giddings and Associates (1994)	From aquifer-test data assuming 200-ft aquifer thickness in Becher (1990, table 7)
Silurian	Rose Hill Formation	Sandstone and limestone	Fracture Siliciclastic	Kshale	Low		0.23					
	Tuscarora Formation	Sandstone	Fracture Siliciclastic	Kshale	Low		0.23					
Ordovician	Juniata	Sandstone and shale	Fracture Siliciclastic	Kshale	Low		0.23					
	Bald Eagle Formation	Sandstone	Fracture Siliciclastic	Kshale	Low		0.23				0.33	
	Reedsville Shale	Shale	Fracture Siliciclastic	Kshale	Low		0.23				0.13	
	Coburn Formation	Limestone	Conduit Carbonate	Kcarb	Low		0.23				0.16	3.3
	Salona Formation	Limestone with shale	Conduit Carbonate	Kcarb	Low		0.23				0.16	3.3
	Nealmont Limestone	Limestone	Conduit Carbonate	LemontK	High		0.23				22	3.3
	Benner Formation	Limestone	Conduit Carbonate	LemontK	High	4.9	0.23					3.3
	Valentine Member of Benner Formation[1]	Limestone	Conduit Carbonate	LemontK	High	4.9	0.23				0.72	3.3
	Snyder Formation	Limestone and dolomite	Conduit Carbonate	LemontK	High	4.9	0.23				11	3.3
	Hatter Formation	Limestone and dolomite	Conduit Carbonate	LemontK	High	4.9	0.23				11	3.3
	Loysburg Formation	Limestone and dolomite	Conduit Carbonate	LemontK	High	4.9	0.23				2.6	3.3
	Bellefonte Dolomite	Dolomite	Fracture Carbonate	Kcarb	Moderate	4.6	1.7	1.3		0.4–2.6	1.6	
	Axemann Limestone	Limestone and dolomite	Conduit Carbonate	Kaxe_ston	Moderate	6.6	1.7				3.3	
	Nittany Dolomite	Dolomite	Fracture Carbonate	Knit	High	11	1.7	9.5		85–490	1.0	300
	Stonehenge Formation	Limestone and dolomite	Conduit Carbonate	Kaxe_ston	Moderate	2.6	4.7				1.8	36

Table 7. Parameters used to represent the hydraulic conductivity of geologic units in the MODFLOW-NWT steady-state model and horizontal hydraulic conductivity values from previous studies for Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania.—Continued

[ft/d, feet per day; ft, foot; max, maximum; —, no data]

Geologic period	Formation[1]	Description	Aquifer type	Parameter name used for hydraulic conductivity of the formation, in this study	K Ranks (based on productivity estimates of Parizek and Filley, 1982)	Hydraulic conductivity (K) values from other studies (ft/d)						
						Model values from Curtin Gap study (Gannett Fleming, 2008)	Model values from Brachet (2004)	Reported median aquifer-test values in Fulton and others (2005)	Model values from study in Blair Co (Lindsey, 2004)	K Parizek (assume 500 ft thick)	Model values K(max) from Todd Giddings and Associates (1994)	From aquifer-test data assuming 200-ft aquifer thickness in Becher (1990, table 7)
Cambrian	Mines Dolomite Member of Gatesburg Formation	Dolomite	Conduit/ Fracture Carbonate	Kgates	High	12	4.7		117	60–120		20
	Upper sandy member of Gatesburg Formation	Dolomite	Diffuse-flow Carbonate	Kgates	High	3.9	4.7	19	117	60–120		20
	Ore Hill Dolomite Member of Gatesburg Formation	Dolomite	Diffuse-flow Carbonate	Kcarb	Moderate	3.9	4.7		117	60–120		20
	Lower sandy member of Gatesburg Formation	Dolomite and sandstone	Diffuse-flow Carbonate	Kcarb	Moderate	3.9	4.7	28	117	60–120		20
	Warrior Formation	Limestone and dolomite	Fracture Carbonate	Kcarb	Moderate		4.7			60–120		

[1]Formation name is from the Pennsylvania Geological Survey and may not conform to usage by the U.S. Geological Survey.

Appendix

Appendix. Results for All of the Calibration Targets for GSFLOW Simulations for Water Years 2000–06

The results for all of the calibration targets for GSFLOW simulations for water years 2000–06 are presented in figures A1–A14. Comparisons are shown for natural log of daily mean streamflow (fig. A1), and annual and monthly streamflow and base flow (figs. A2–A12). Groundwater levels and annual mean water levels in observation wells are shown in figures A13 and A14.

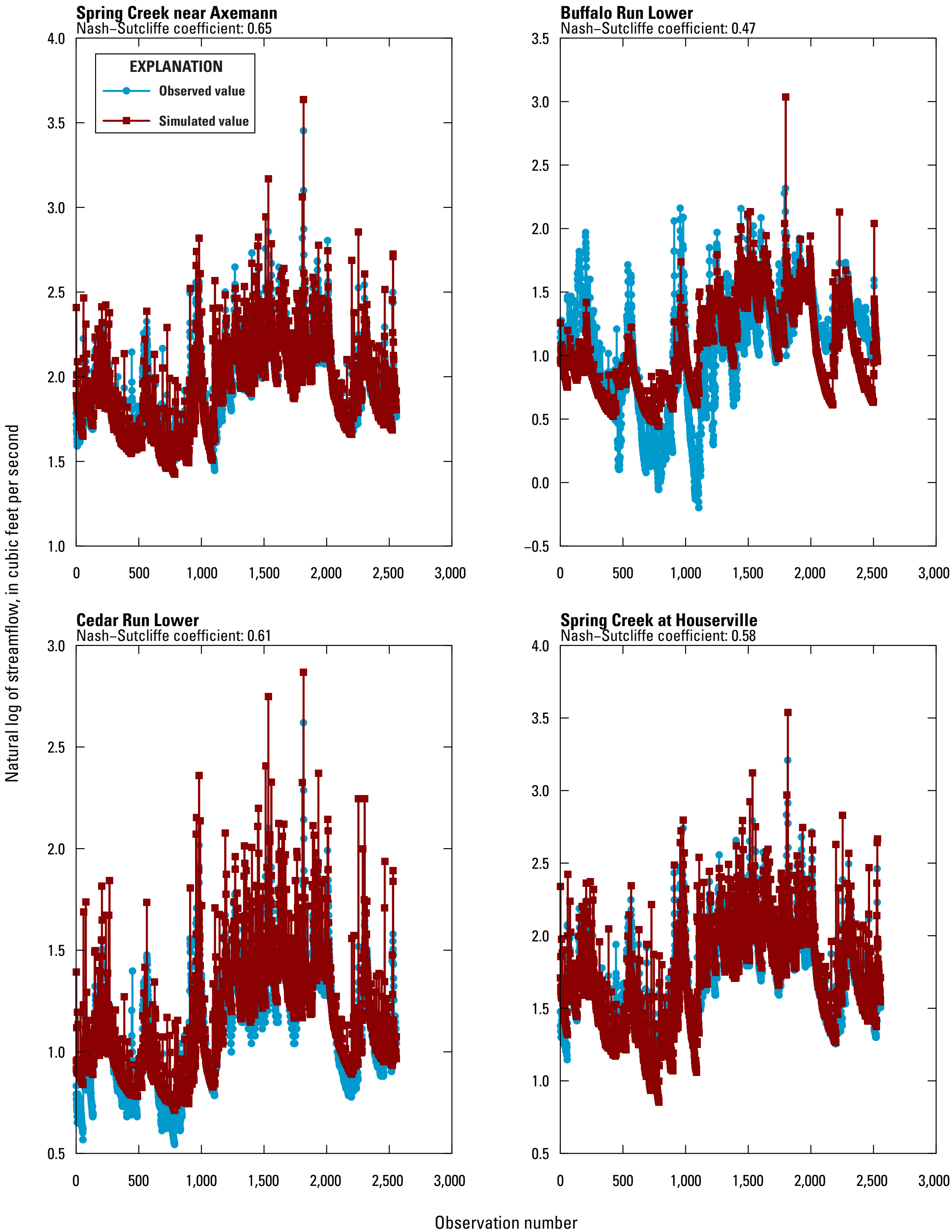

Figure A1. Observations and GSFLOW simulations of the natural log of daily streamflow at 11 streamgages in the Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania, water years 2000–06.

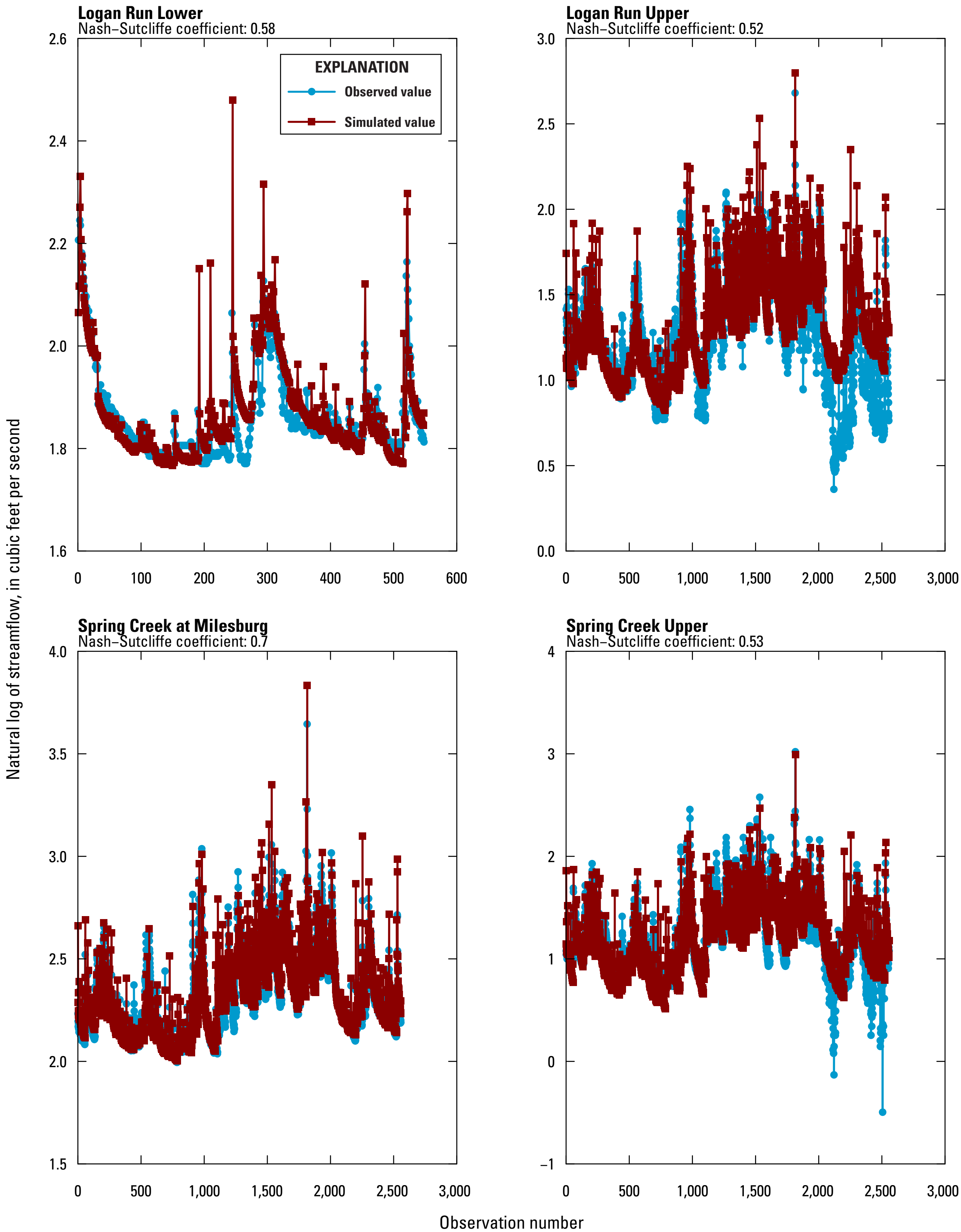

Figure A1. Observations and GSFLOW simulations of the natural log of daily streamflow at 11 streamgages in the Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania, water years 2000–06.—Continued

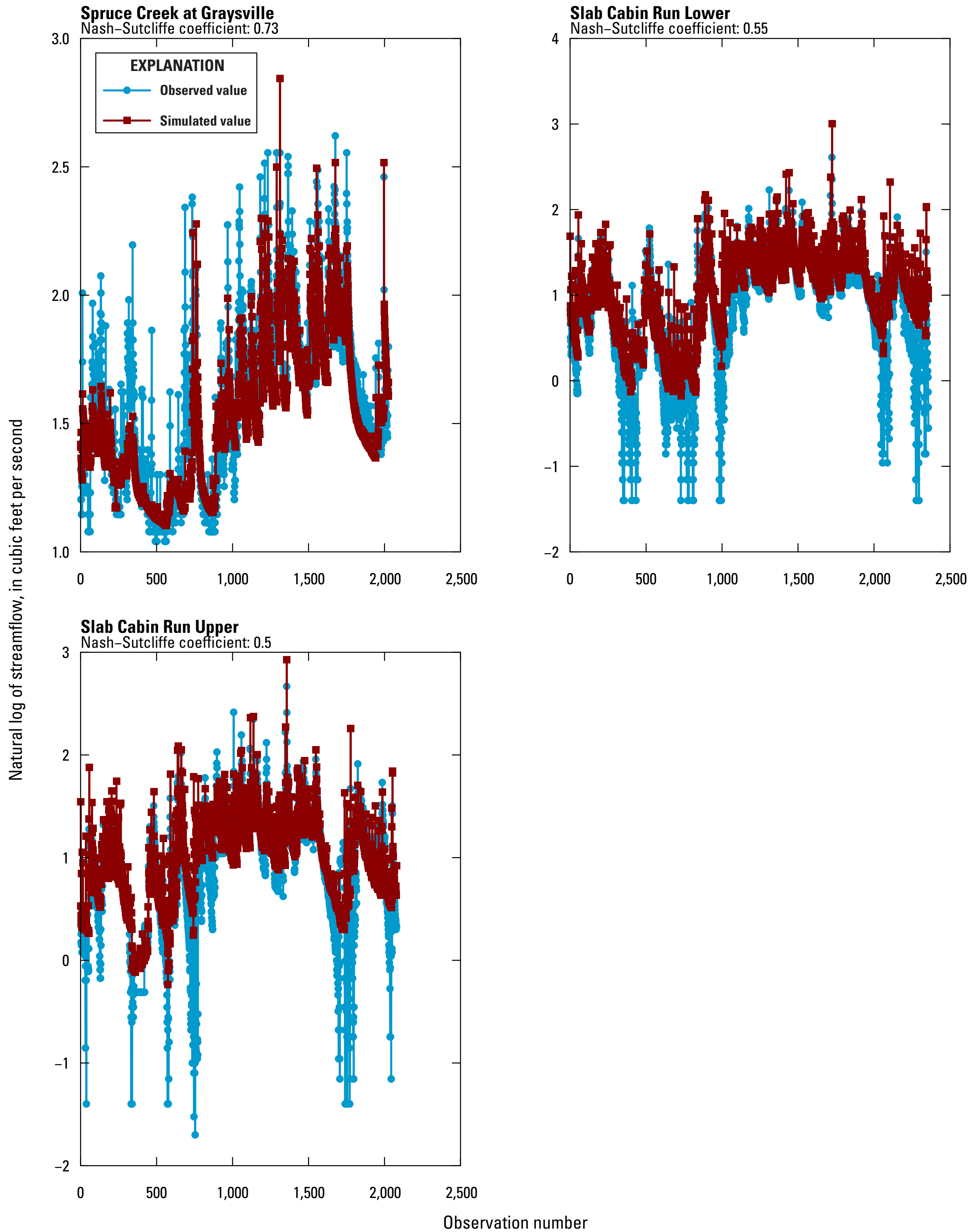

Figure A1. Observations and GSFLOW simulations of the natural log of daily streamflow at 11 streamgages in the Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania, water years 2000–06.—Continued

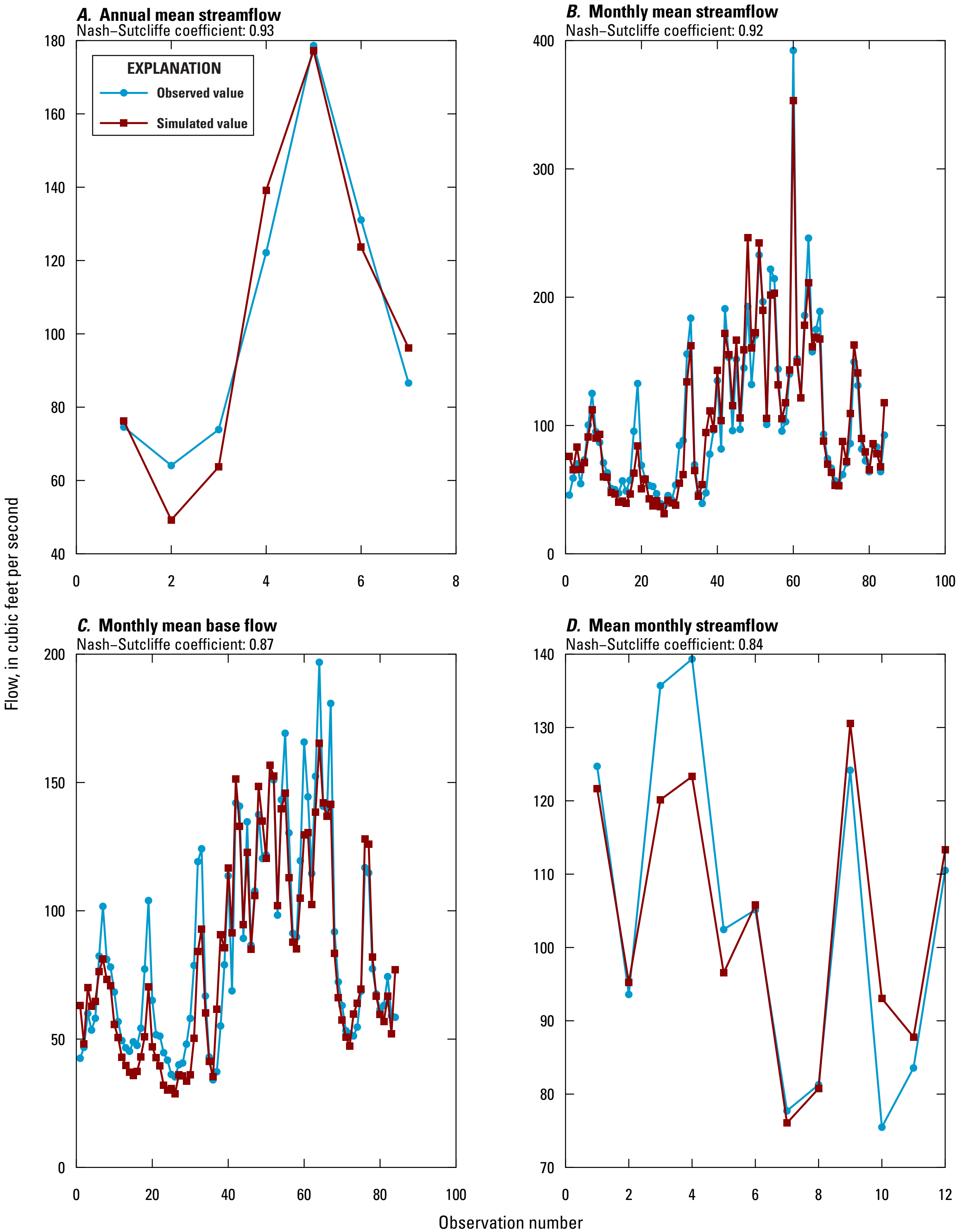

Figure A2. Observations and GSFLOW simulations of *A*, annual mean streamflow, *B*, monthly mean streamflow, *C*, monthly mean base flow, and *D*, mean monthly streamflow at Spring Creek near Axemann in the Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania, water years 2000–06.

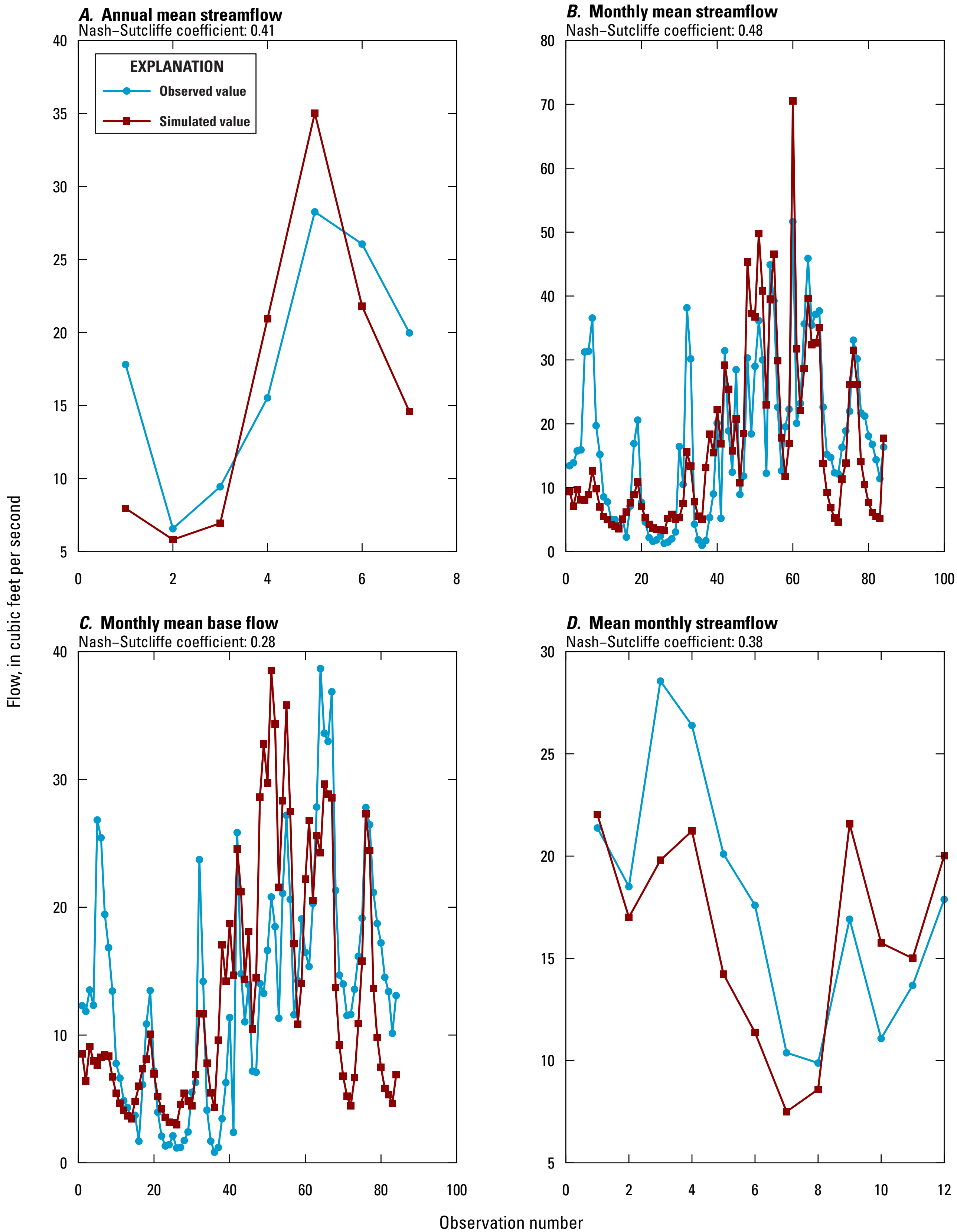

Figure A3. Observations and GSFLOW simulations of *A*, annual mean streamflow, *B*, monthly mean streamflow, *C*, monthly mean base flow, and *D*, mean monthly streamflow at Buffalo Run Lower in the Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania, water years 2000–06.

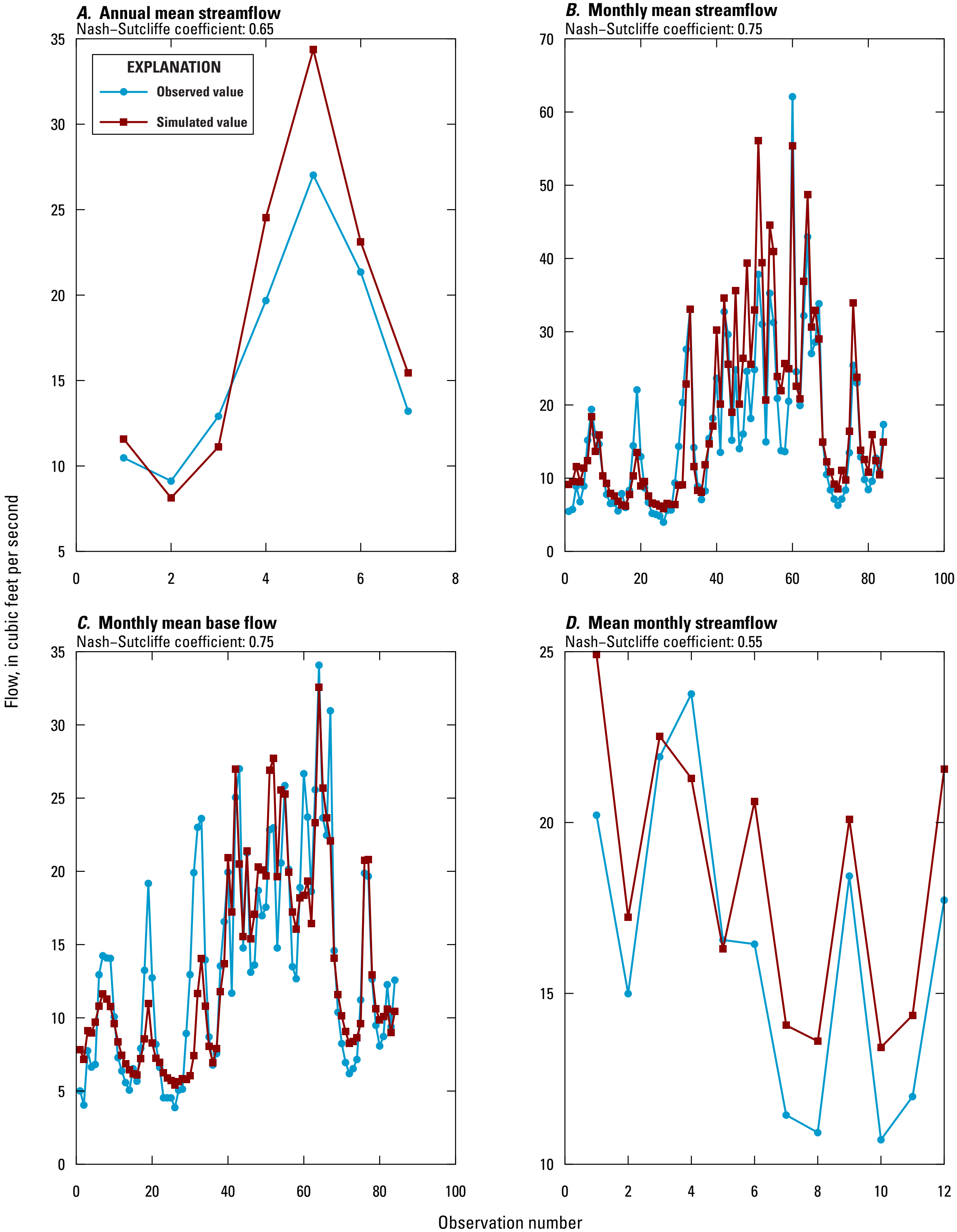

Figure A4. Observations and GSFLOW simulations of *A*, annual mean streamflow, *B*, monthly mean streamflow, *C*, monthly mean base flow, and *D*, mean monthly streamflow at Cedar Run Lower in the Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania, water years 2000–06.

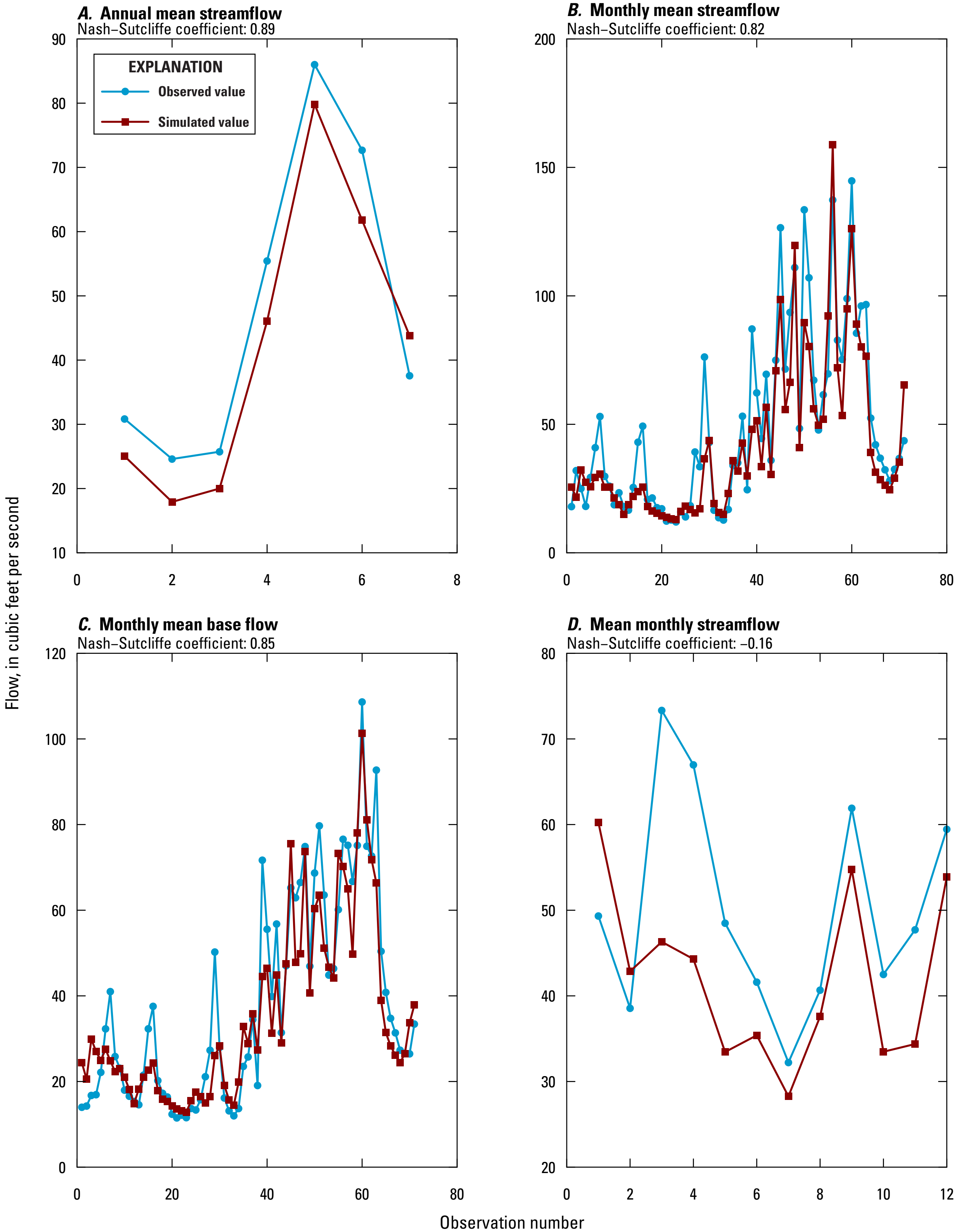

Figure A5. Observations and GSFLOW simulations of *A*, annual mean streamflow, *B*, monthly mean streamflow, *C*, monthly mean base flow, and *D*, mean monthly streamflow at Spruce Creek at Graysville in the Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania, water years 2000–06.

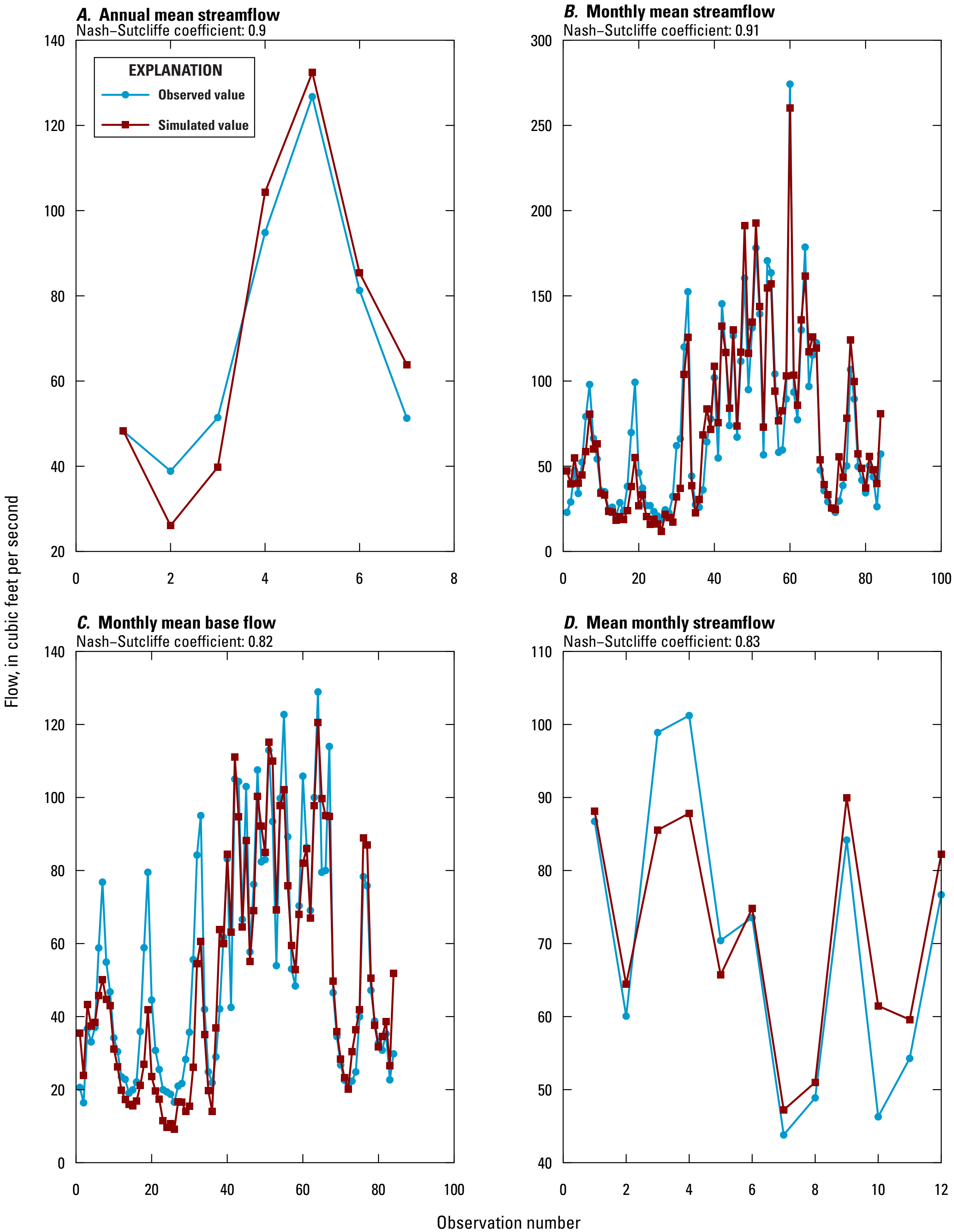

Figure A6. Observations and GSFLOW simulations of *A*, annual mean streamflow, *B*, monthly mean streamflow, *C*, monthly mean base flow, and *D*, mean monthly streamflow at Spring Creek at Houserville in the Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania, water years 2000–06.

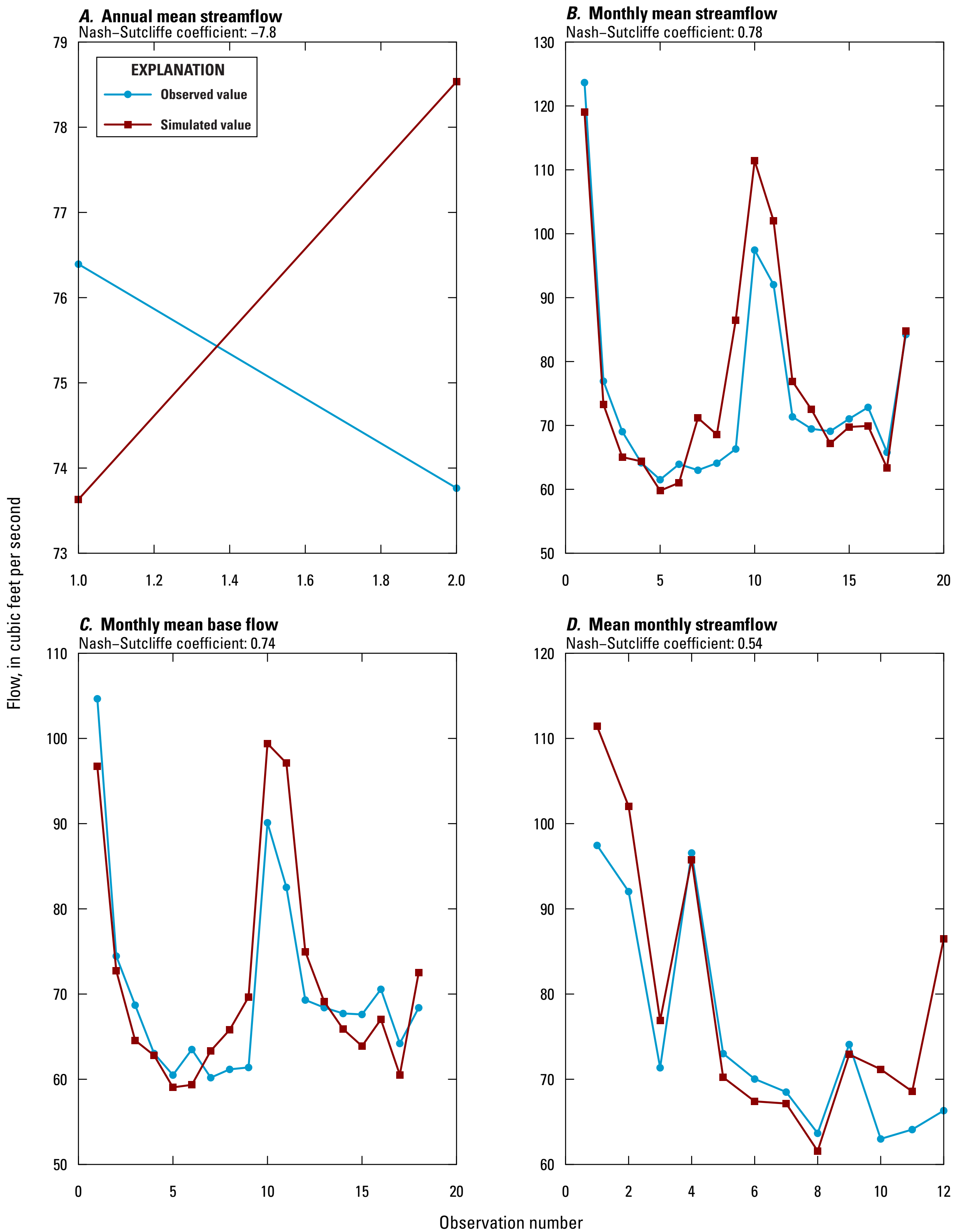

Figure A7. Observations and GSFLOW simulations of *A*, annual mean streamflow, *B*, monthly mean streamflow, *C*, monthly mean base flow, and *D*, mean monthly streamflow at Logan Branch Lower in the Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania, water years 2000–06.

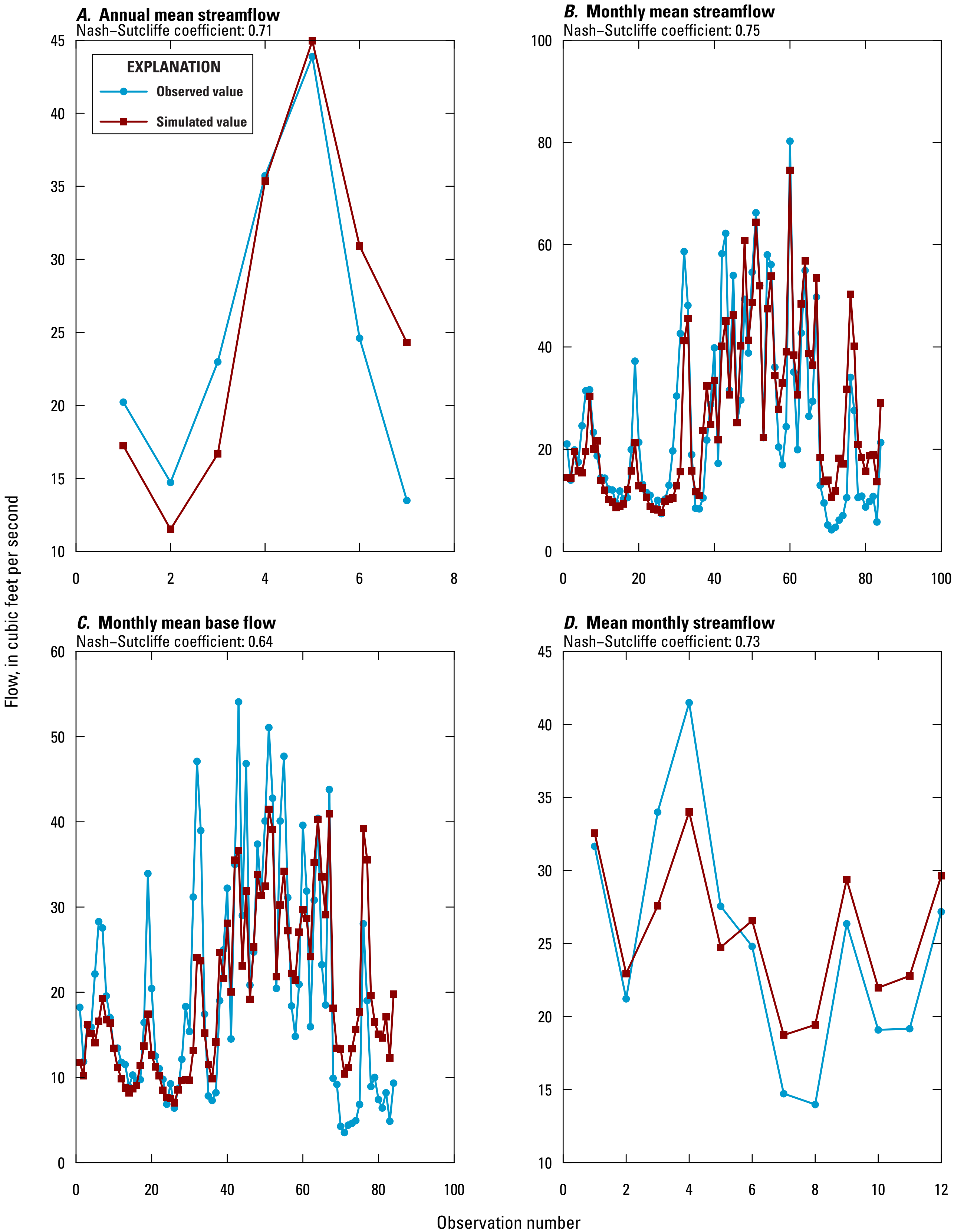

Figure A8. Observations and GSFLOW simulations of *A*, annual mean streamflow, *B*, monthly mean streamflow, *C*, monthly mean base flow, and *D*, mean monthly streamflow at Logan Branch Upper in the Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania, water years 2000–06.

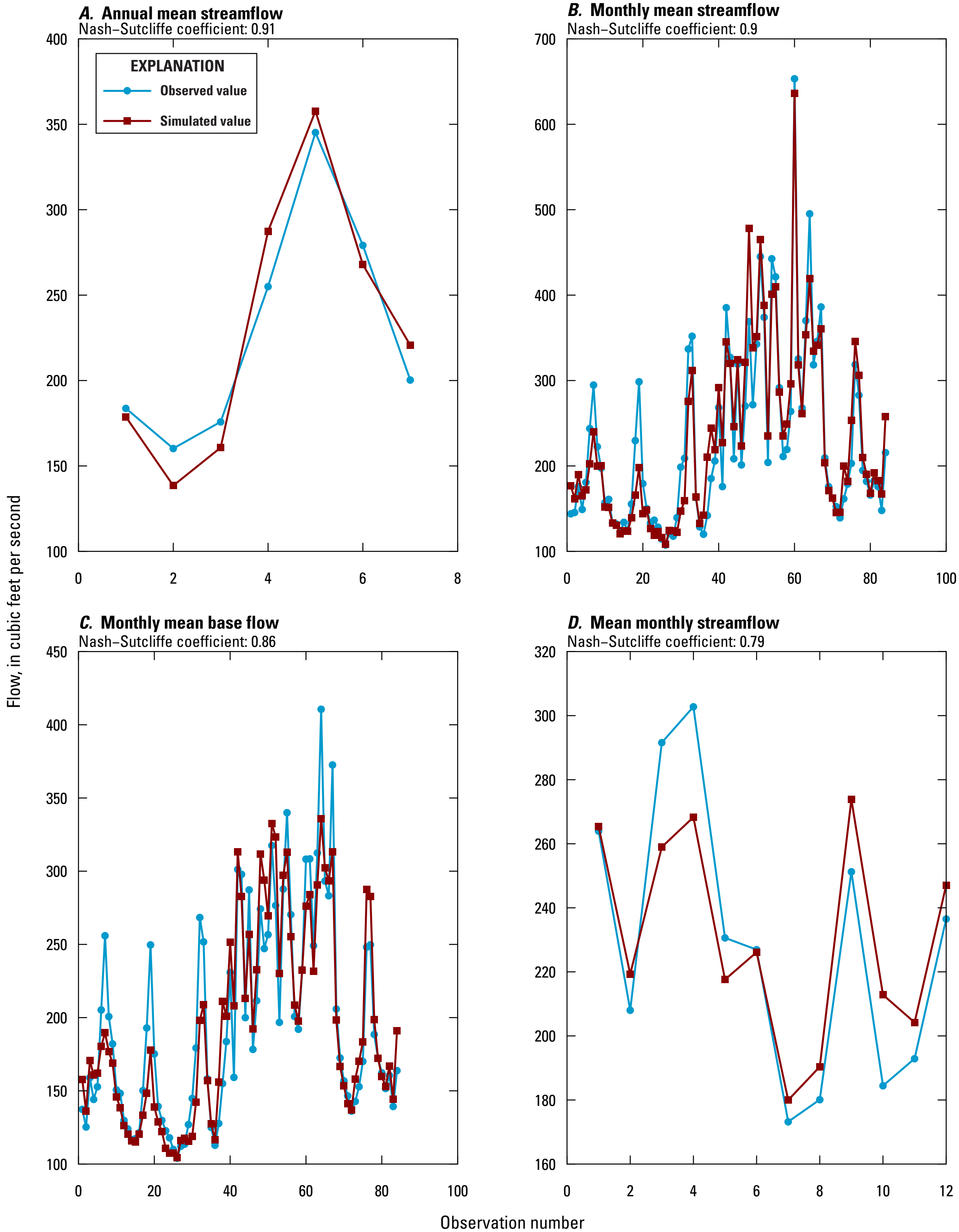

Figure A9. Observations and GSFLOW simulations of *A*, annual mean streamflow, *B*, monthly mean streamflow, *C*, monthly mean base flow, and *D*, mean monthly streamflow at Spring Creek at Milesburg in the Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania, water years 2000–06.

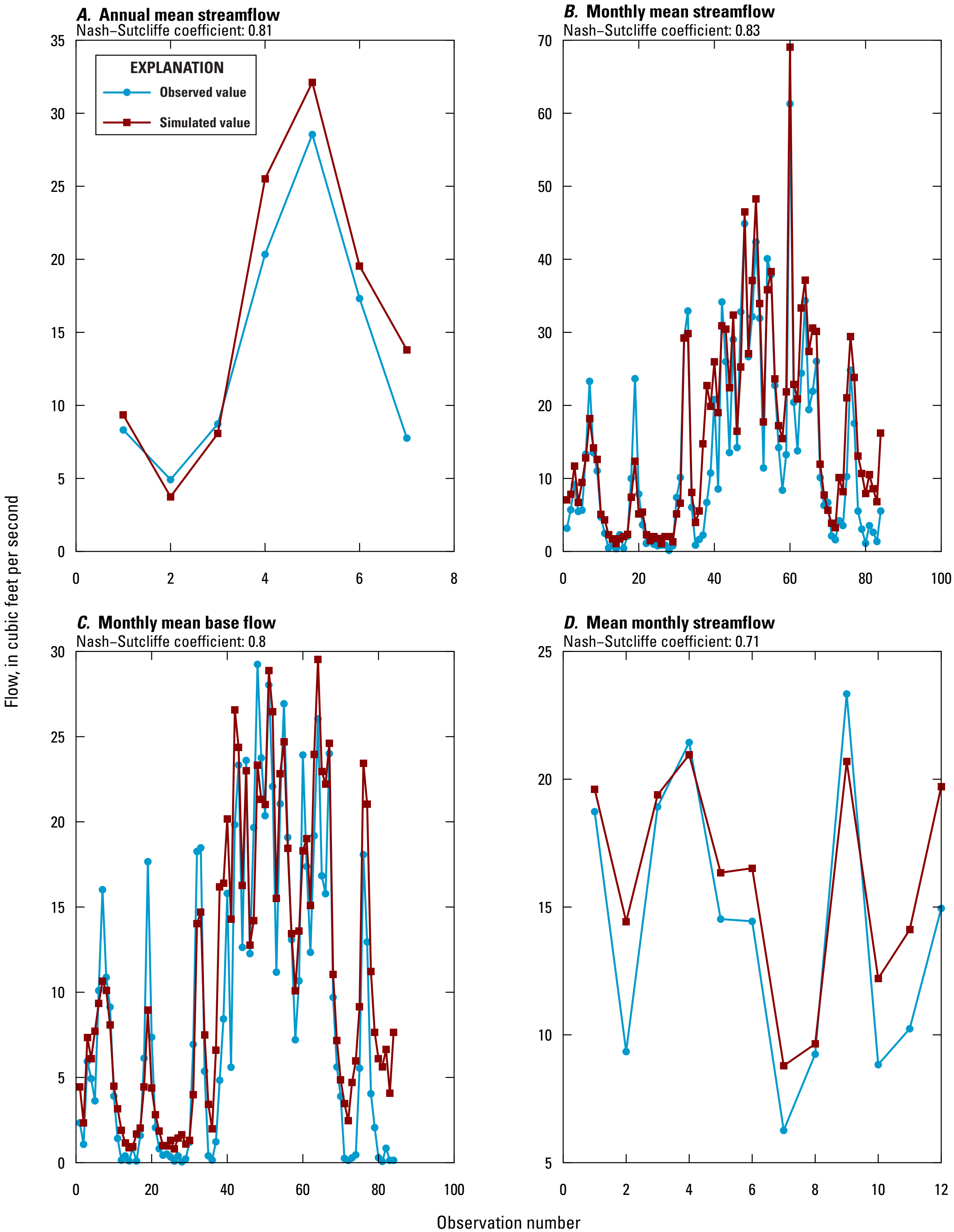

Figure A10. Observations and GSFLOW simulations of *A*, annual mean streamflow, *B*, monthly mean streamflow, *C*, monthly mean base flow, and *D*, mean monthly streamflow at Slab Cabin Run Lower in the Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania, water years 2000–06.

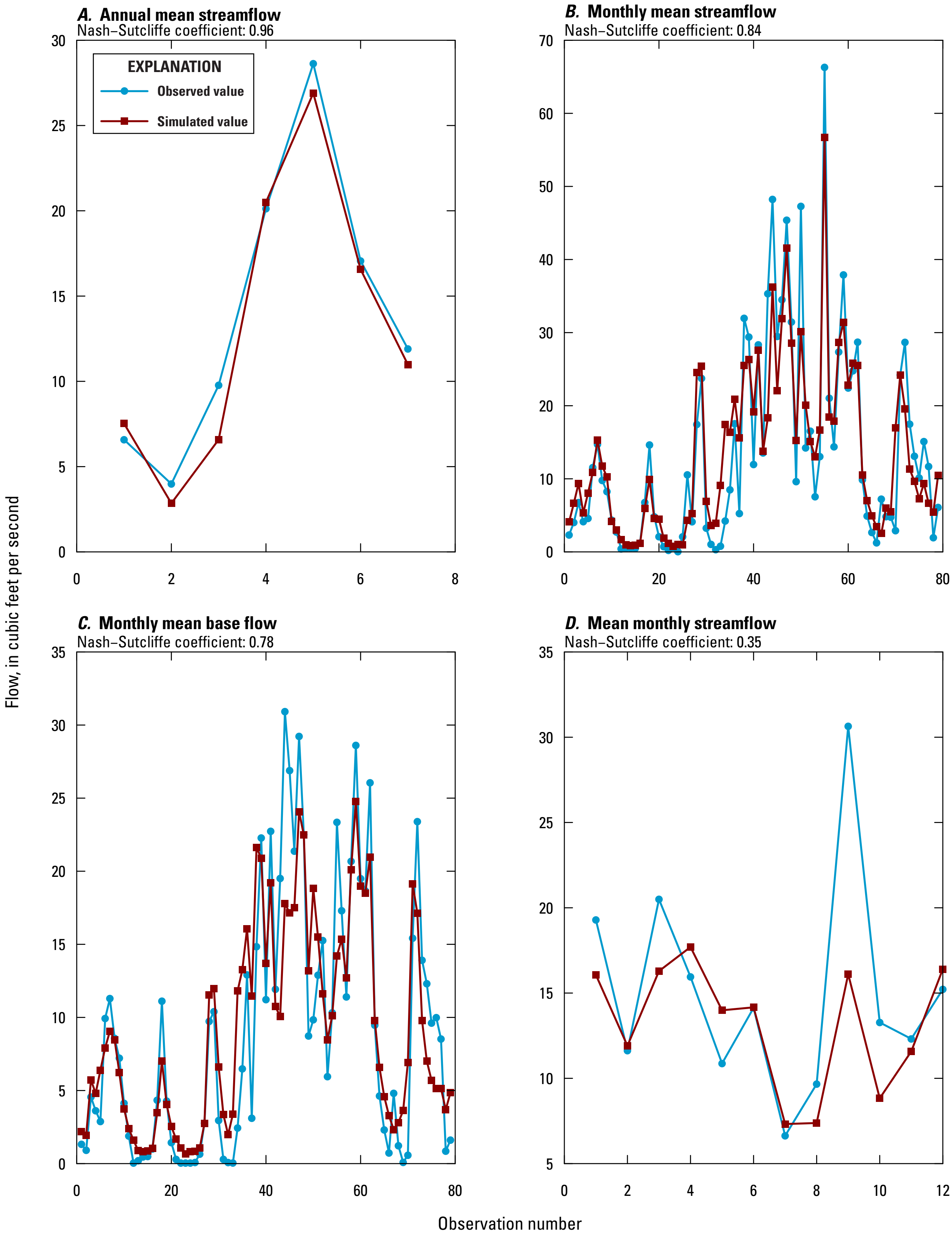

Figure A11. Observations and GSFLOW simulations of *A*, annual mean streamflow, *B*, monthly mean streamflow, *C*, monthly mean base flow, and *D*, mean monthly streamflow at Slab Cabin Run Upper in the Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania, water years 2000–06.

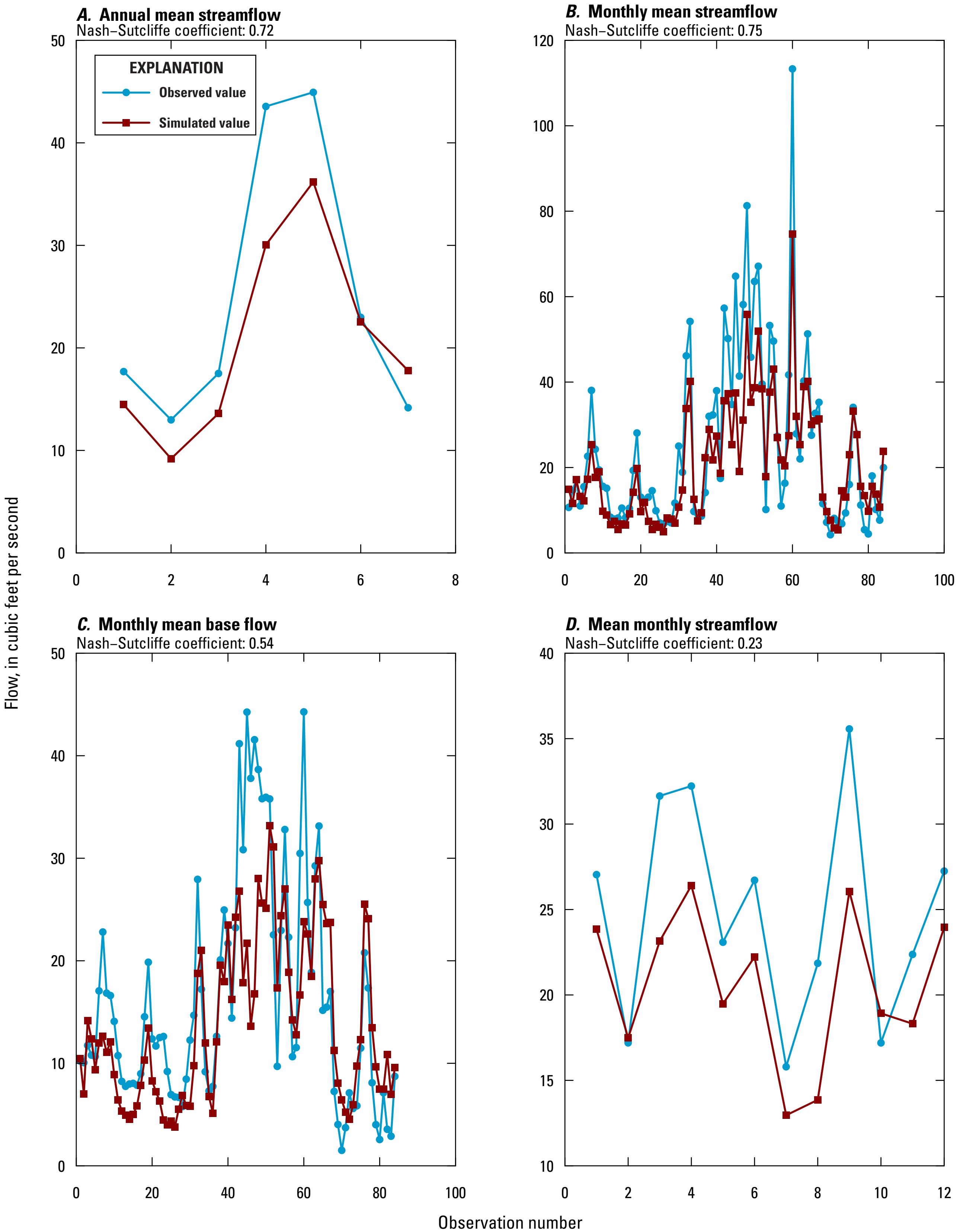

Figure A12. Observations and GSFLOW simulations of *A*, annual mean streamflow, *B*, monthly mean streamflow, *C*, monthly mean base flow, and *D*, mean monthly streamflow at Spring Creek Upper in the Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon Counties, Pennsylvania, water years 2000–06.

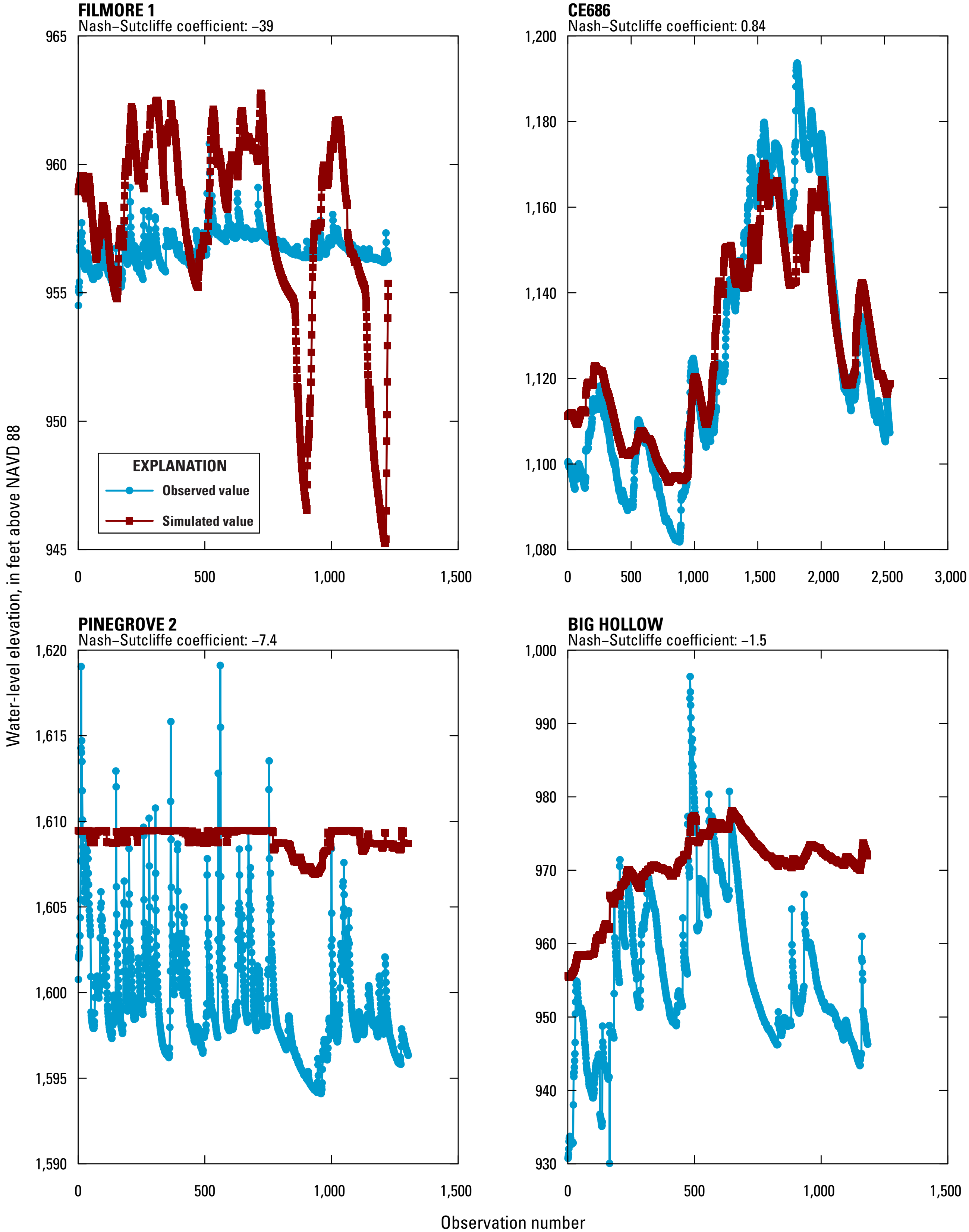

Figure A13. Observations and GSFLOW simulations of groundwater levels in selected wells in the Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon counties, Pennsylvania, water years 2000–06.

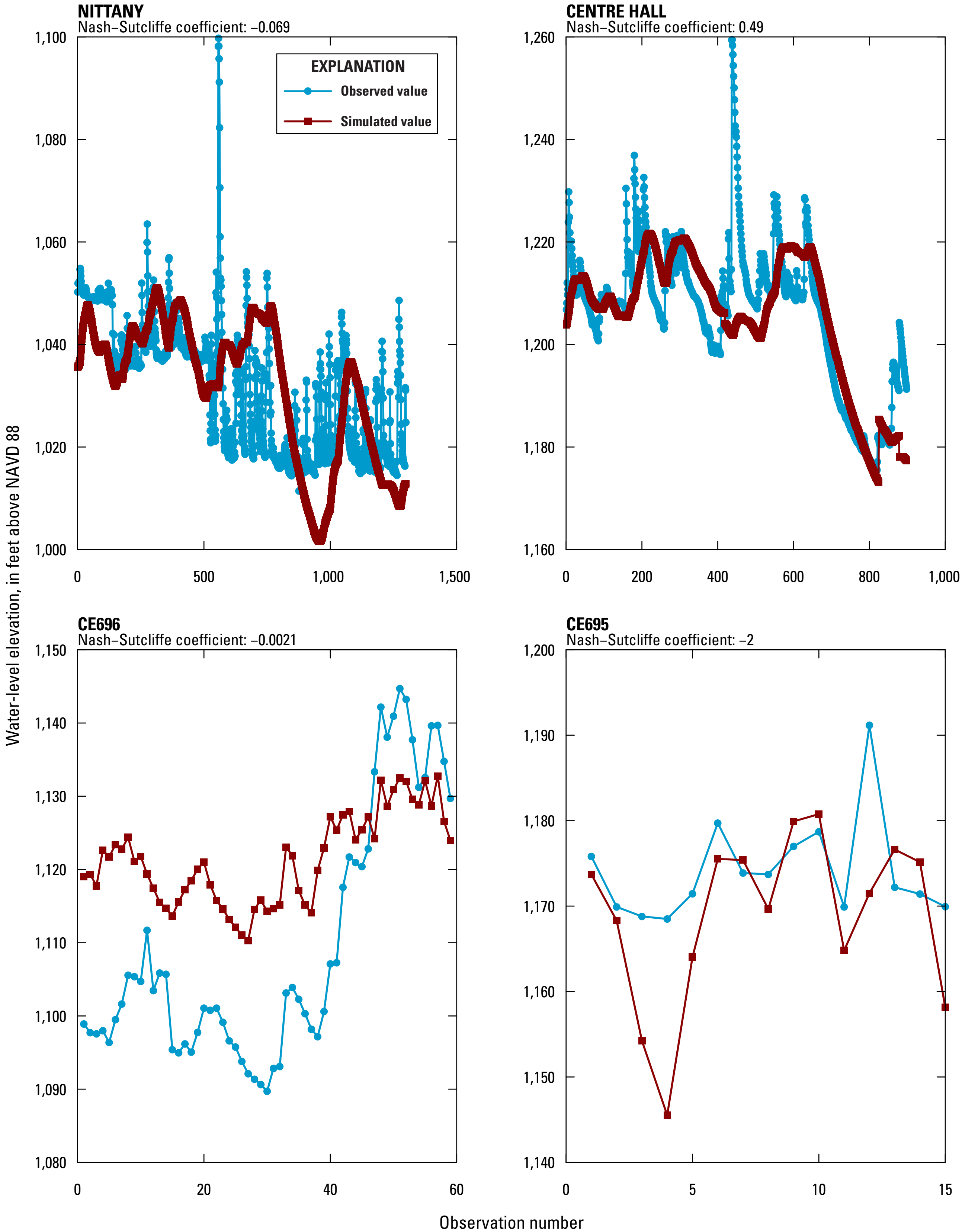

Figure A13. Observations and GSFLOW simulations of groundwater levels in selected wells in the Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon counties, Pennsylvania, water years≈2000–06.—Continued

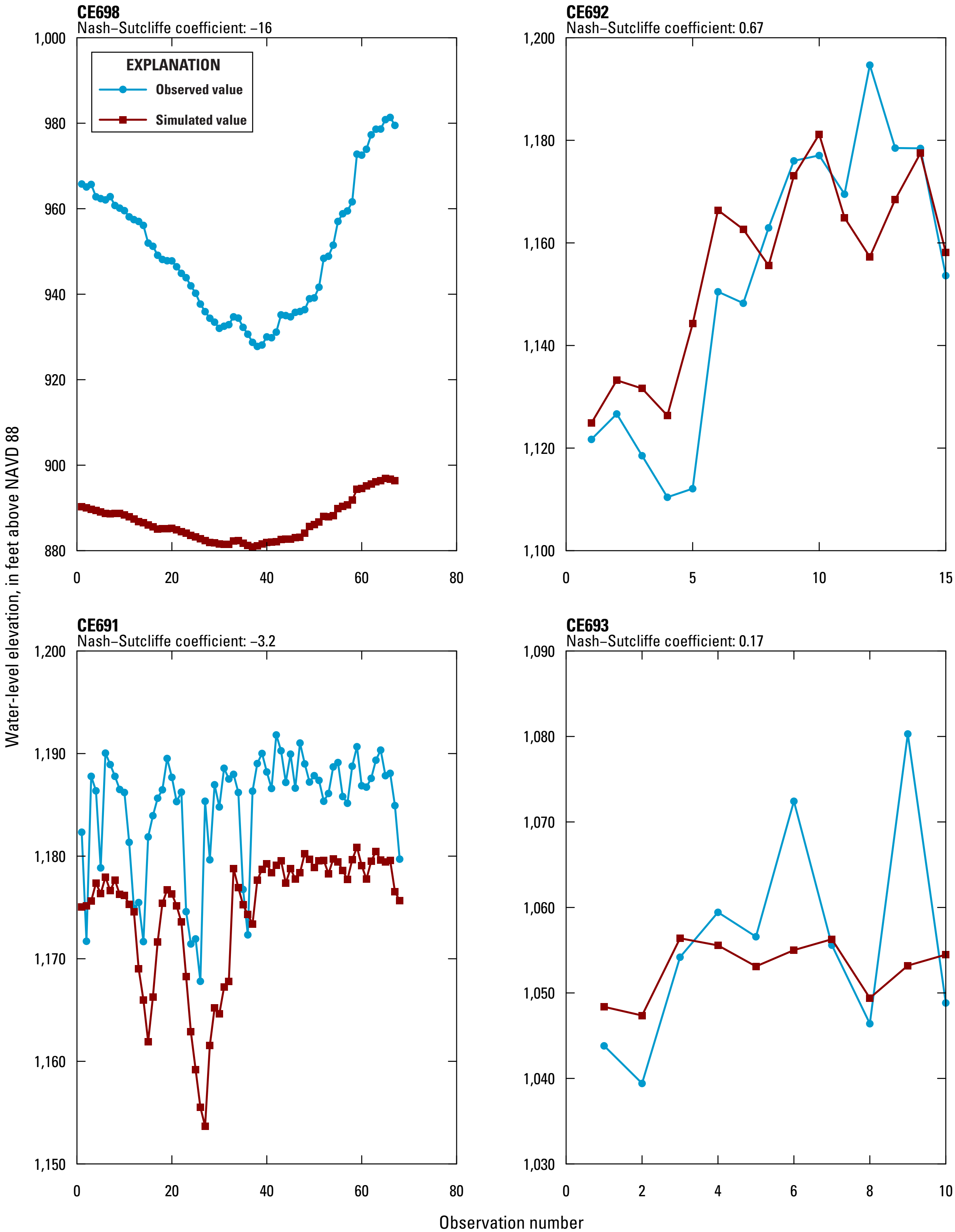

Figure A13. Observations and GSFLOW simulations of groundwater levels in selected wells in the Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon counties, Pennsylvania, water years≈2000–06.—Continued

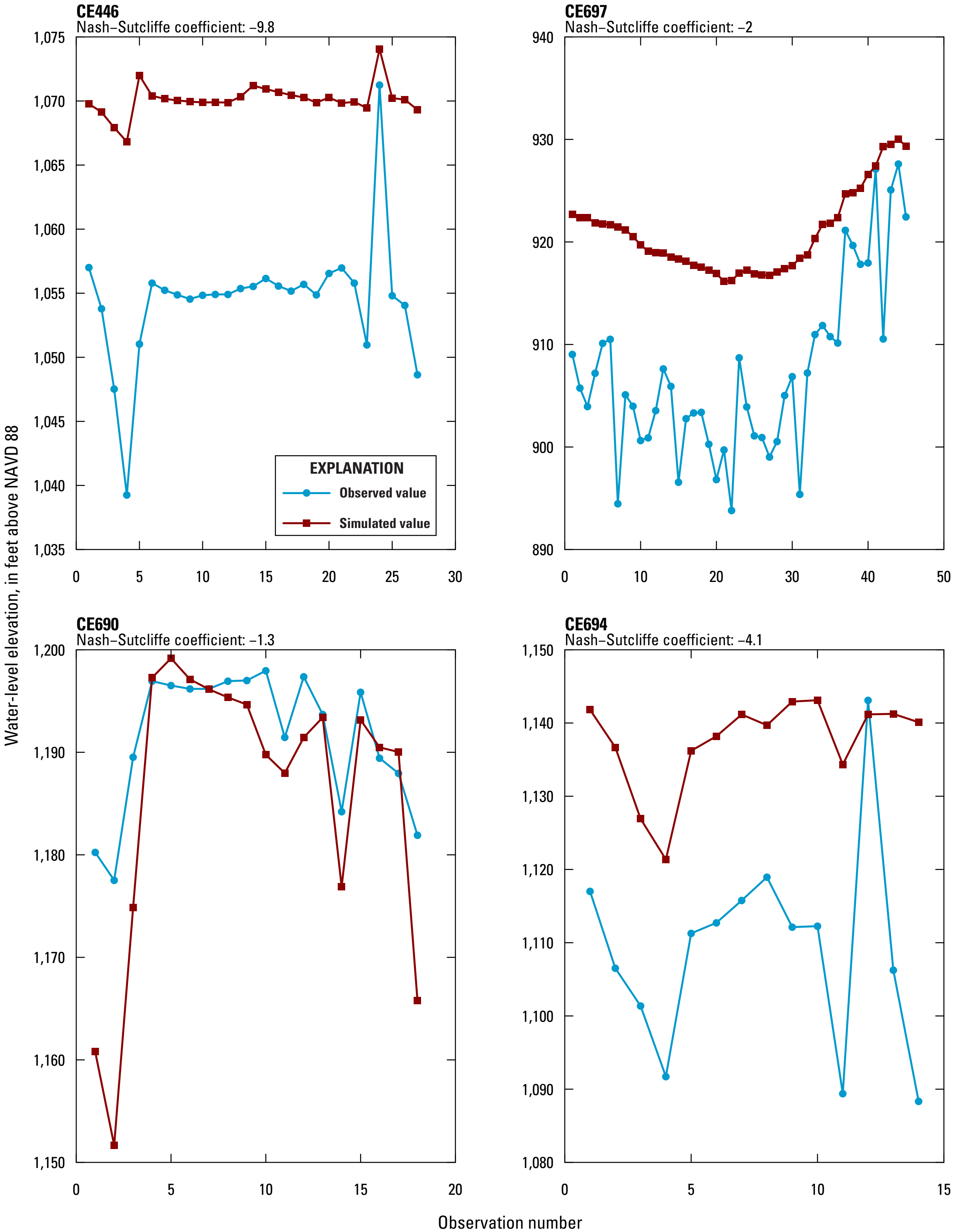

Figure A13. Observations and GSFLOW simulations of groundwater levels in selected wells in the Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon counties, Pennsylvania, water years≈2000–06.—Continued

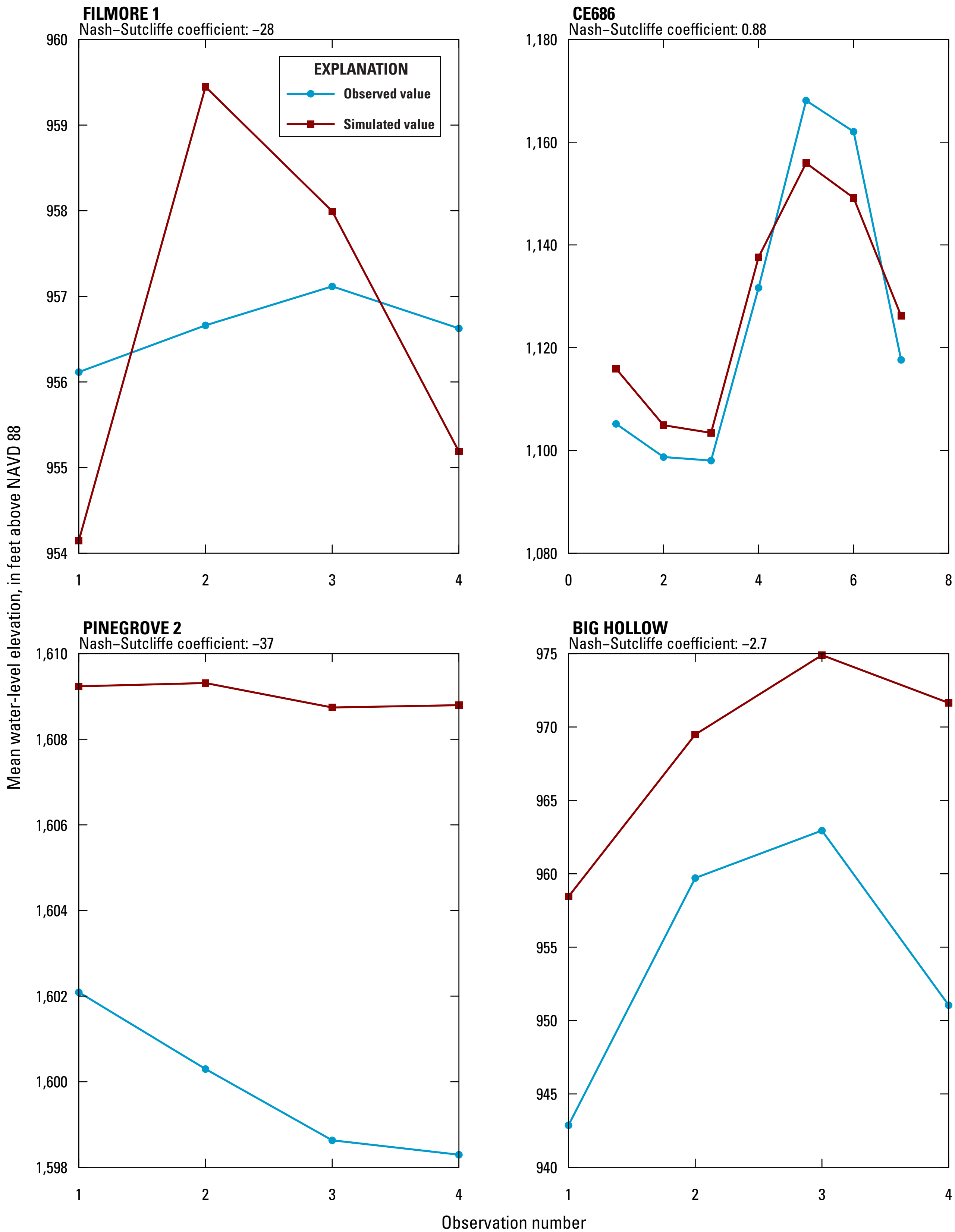

Figure A14. Observations and GSFLOW simulations of annual mean groundwater levels in selected wells in the Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon counties, Pennsylvania, water years 2000–06.

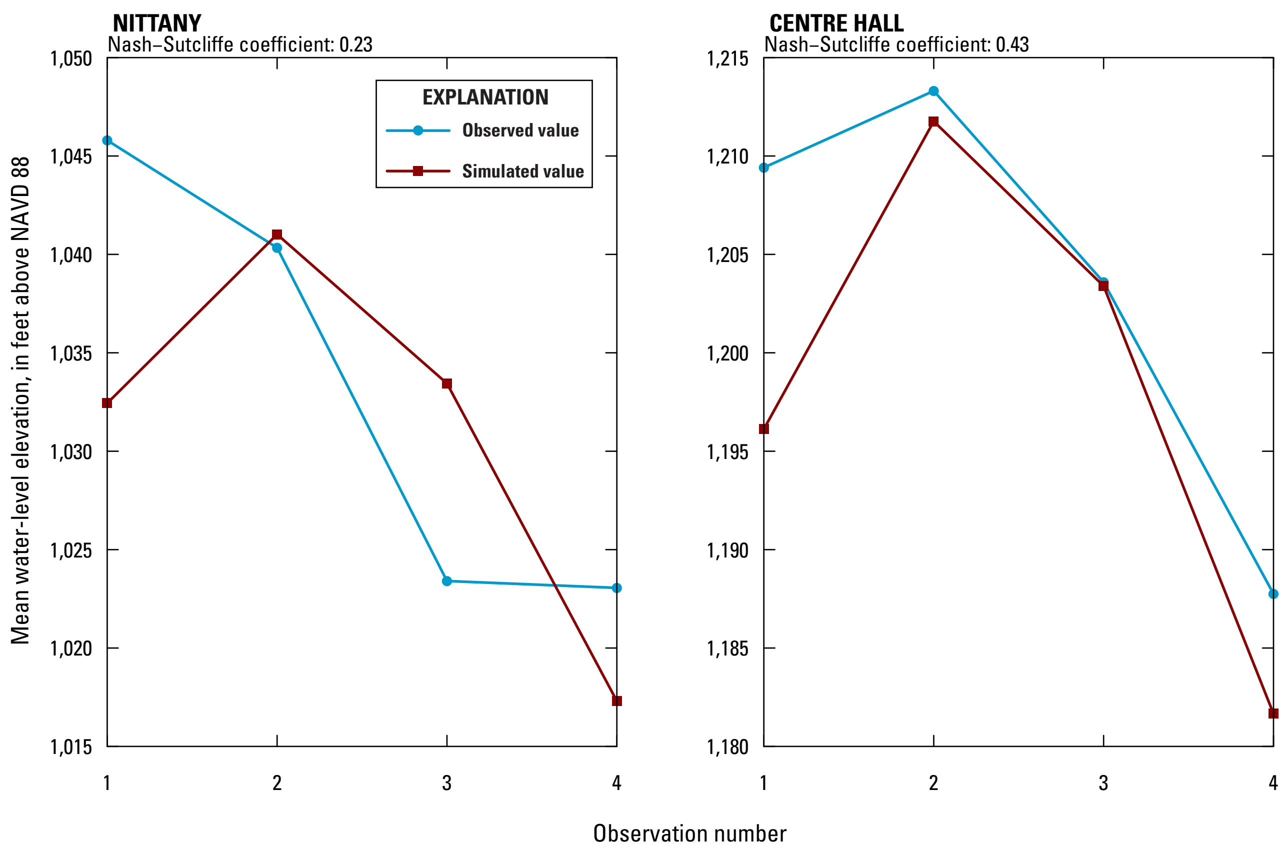

Figure A14. Observations and GSFLOW simulations of annual mean groundwater levels in selected wells in the Spring Creek and Nittany Creek Basins and parts of the Spruce Creek Basin, Centre and Huntingdon counties, Pennsylvania, water years 2000–06.—Continued

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