Simulated Water Budgets and Ground-Water/Surface-Water Interactions in Bushkill and Parts of Monocacy Creek Watersheds, Northampton County, Pennsylvania—A Preliminary Study with Identification of Data Needs

By Dennis W. Risser

In cooperation with the
Pennsylvania Department of Environmental Protection

Open-File Report 2006-1143

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

Report Documentation Page		*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE **2006**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **Simulated Water Budgets and Ground-Water/Surface-Water Interactions in Bushkill and Parts of Monocacy Creek Watersheds, Northampton County, Pennsylvania--A Preliminary Study With Identification of Data Needs**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **U.S. Department of the Interior 1849 C Street, NW Washington, DC 20240**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release, distribution unlimited**		
13. SUPPLEMENTARY NOTES **The original document contains color images.**		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**31**	

U.S. Department of the Interior
P. Lynn Scarlett, Acting Secretary

U.S. Geological Survey
P. Patrick Leahy, Acting Director

U.S. Geological Survey, Reston, Virginia: 2006

For sale by U.S. Geological Survey, Information Services
Box 25286, Denver Federal Center
Denver, CO 80225

For more information about the USGS and its products:
Telephone: 1-888-ASK-USGS
World Wide Web: *http://www.usgs.gov/*

Suggested citation:

Risser, D.W., 2006, Simulated water budgets and ground-water/surface-water interactions in Bushkill and parts of Monocacy Creek watersheds, Northampton County, Pennsylvania—A preliminary study with identification of data needs: U.S. Geological Survey Open-File Report 2006-1143, 31 p.

Contents

Figures

Tables

Conversion Factors and Datum

Multiply	By	To obtain
Length		
inch (in.)	0.0254	meter (m)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
Flow rate		
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
Hydraulic conductivity		
foot per day (ft/d)	0.3048	meter per day (m/d)

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

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29), unless otherwise noted.

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

Simulated Water Budgets and Ground-Water/Surface-Water Interactions in Bushkill and Parts of Monocacy Creek Watersheds, Northampton County, Pennsylvania--A Preliminary Study with Identification of Data Needs

By Dennis W. Risser

Abstract

This report, prepared in cooperation with the Pennsylvania Department of Environmental Protection, Office of Mineral Resources Management, provides a preliminary analysis of water budgets and generalized ground-water/surface-water interactions for Bushkill and parts of Monocacy Creek watersheds in Northampton County, Pa., by use of a ground-water flow model. Bushkill Creek watershed was selected for study because it has areas of rapid growth, ground-water withdrawals from a quarry, and proposed stream-channel modifications, all of which have the potential for altering ground-water budgets and the interaction between ground water and streams.

Preliminary 2-dimensional, steady-state simulations of ground-water flow by the use of MODFLOW are presented to show the status of work through September 2005 and help guide ongoing data collection in Bushkill Creek watershed. Simulations were conducted for (1) predevelopment conditions, (2) a water table lowered for quarry operations, and (3) anthropogenic changes in hydraulic conductivity of the streambed and aquifer. Preliminary results indicated under predevelopment conditions, the divide between the Bushkill and Monocacy Creek ground-water basins may not have been coincident with the topographic divide and as much as 14 percent of the ground-water discharge to Bushkill Creek may have originated from recharge in the Monocacy Creek watershed. For simulated predevelopment conditions, Schoeneck Creek and parts of Monocacy Creek were dry, but Bushkill Creek was gaining throughout all reaches.

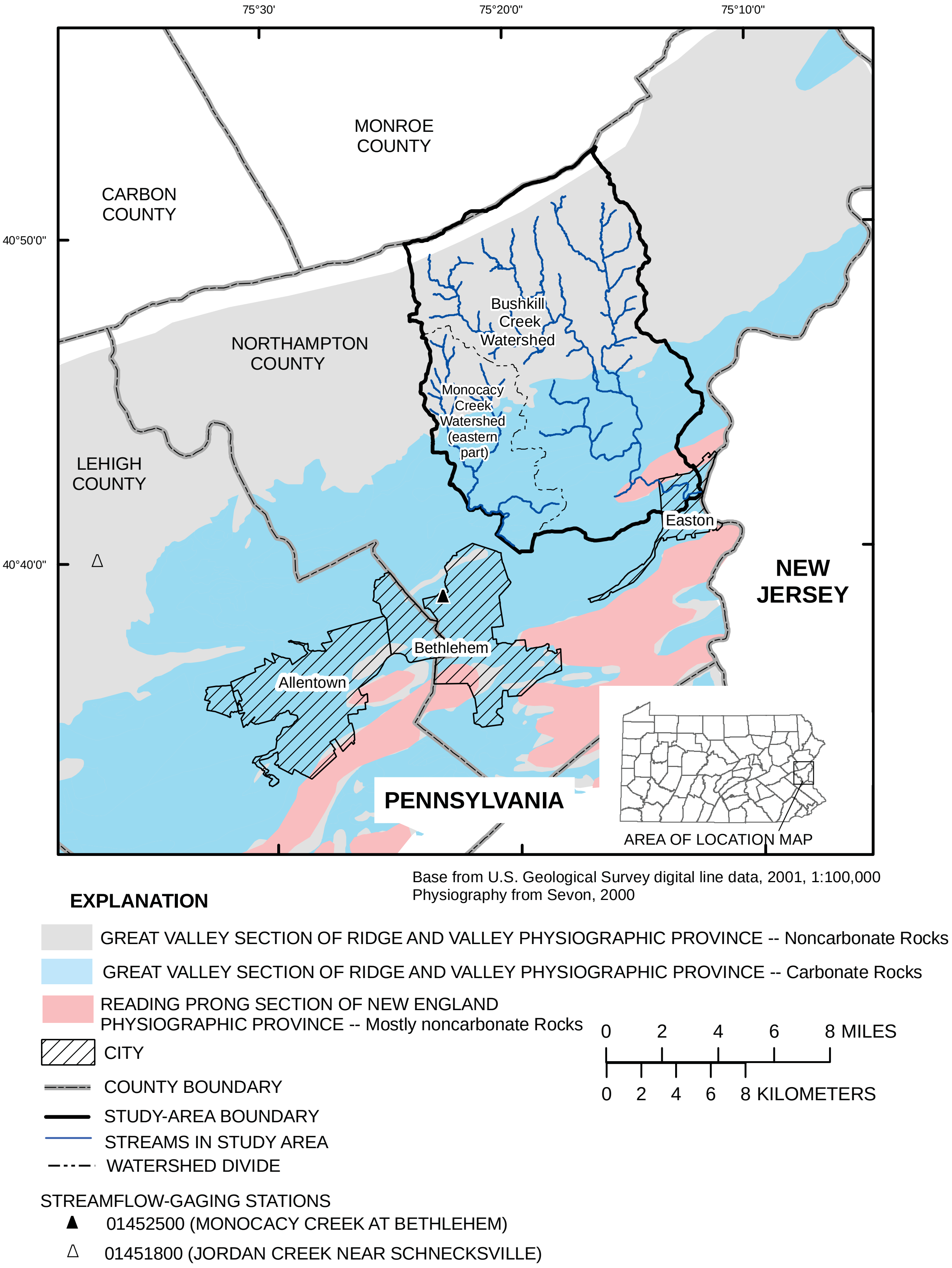
Simulated lowering of the deepest quarry sump to an altitude of 147 feet for quarry operations caused ground-water recharge and streamflow leakage to be diverted to the quarry throughout about 14 square miles and caused reaches of Bushkill and Little Bushkill Creeks to change from gaining to losing streams. Lowering the deepest quarry sump to an altitude of 100 feet caused simulated ground-water discharge to the quarry to increase about 4 cubic feet per second. Raising the deepest sump to an altitude of 200 feet caused the simulated discharge to the quarry to decrease about 14 cubic feet per second.

Decreasing the hydraulic conductivity of the streambed of Bushkill Creek in the reach of large losses of flow caused simulated ground-water levels to decline and ground-water discharge to a quarry to decrease from 74 to 45 cubic feet per second. Decreasing the hydraulic conductivity of a hypothesized highly transmissive zone with a plug of relatively impermeable material caused ground-water levels to increase east of the plug and decline west of the plug, and decreased the discharge to a quarry from 74 to 53 cubic feet per second.

Preliminary results of the study have significant limitations, which need to be recognized by the user. The results demonstrated the usefulness of ground-water modeling with available data sets, but as more data become available through field studies, a more complete evaluation could be conducted of the preliminary assumptions in the conceptual model, model sensitivity, and effects of boundary conditions. Additional streamflow and ground-water-level measurements would be needed to better quantify recharge and aquifer properties, particularly the anisotropy of carbonate rocks. Measurements of streamflow losses at average, steady-state hydrologic conditions could provide a more accurate estimate of ground-water recharge from this source, which directly affects water budgets and contributing areas simulated by the model.

Introduction

Areas in Northampton County underlain by carbonate bedrock have some of the highest densities of sinkhole occurrence in Pennsylvania (Kochanov and Reese, 2003), posing an environmental hazard in the rapidly developing Allentown/Bethlehem/Easton corridor (fig. 1). For example, during the past 6 years, sinkholes within the channel of Bushkill Creek damaged two state highway bridges and increased losses of streamflow from the creek. Natural and human-induced changes in the hydrologic system have been cited as possible causative factors in sinkhole development (Earth Tech, Inc., 2002, p. 108), but hydrologic data that predate alterations to stream channels and large ground-water withdrawals are lacking. Therefore, ground-water modeling was proposed as a method for estimating predevelopment ground-water conditions and evaluating potential effects of sinkhole-mitigation activities.



Base from U.S. Geological Survey digital line data, 2001, 1:100,000
Physiography from Sevon, 2000

Figure 1. Location of Bushkill Creek watershed within lithologic units of the Great Valley Section of the Ridge and Valley Physiographic Province, Northampton County, Pennsylvania.

This study, conducted by the U.S. Geological Survey (USGS) in cooperation with the Pennsylvania Department of Environmental Protection (PaDEP), Office of Minerals Resource Management, provides a preliminary analysis of water budgets and ground-water/surface-water interactions in part of Northampton County. A comprehensive regional evaluation of the ground-water resources in the karst terrain of the Great Valley in eastern Pennsylvania would require additional water-table mapping, streamflow measurements, and tracer studies. Such a regional evaluation would provide scientific information to managers for planning sustainable development, water use, and resource extraction while minimizing losses from natural hazards. Bushkill Creek watershed was selected for study because it has areas of rapid growth, large ground-water withdrawals from a quarry, and proposed stream-channel modifications to mitigate sinkhole development.

Purpose and Scope

This report provides preliminary results from a ground-water flow model for Bushkill and parts of Monocacy Creek watersheds in Northampton County. The report describes model construction, data used to adjust hydrologic parameters, and simulations of water budgets and ground-water/surface-water interactions. Preliminary simulations are presented for (1) predevelopment conditions, (2) a water table lowered for quarry operations, and (3) anthropogenic changes in hydraulic conductivity of the streambed and aquifer. The purpose of reporting on the preliminary results is to present the status of work using data available through September 2005 and to help guide ongoing data collection in Bushkill Creek watershed. The results are preliminary because the model is being revised as additional water-level and streamflow data become available.

Previous Investigations

The ground-water resources in Northampton County were summarized briefly in Hall (1934) and Miller and others (1939). The hydrology of the Martinsburg Formation of Lehigh and Northampton Counties was studied by Poth (1972); his work included an analysis of water-bearing zones and specific capacity of wells. Wood and others (1972) described the characteristics of the carbonate-rock aquifers and ground-water/surface-water interactions in the adjacent Lehigh County. A detailed study of ground-water conditions in the vicinity of a large cement quarry in the study area was conducted by Earth Tech, Inc. (2002). Their report included a summary of previous investigations, geologic and geophysical studies, aquifer testing, ground-water monitoring, and surface-water monitoring. A ground-water flow model by Hazlett-Kincaid, Inc. (2002), which was also included in the Earth Tech (2002) report, was used to estimate the effect of quarry dewatering on the water-table configuration but did not simulate streams, so ground-water/surface-water interactions were not simulated.

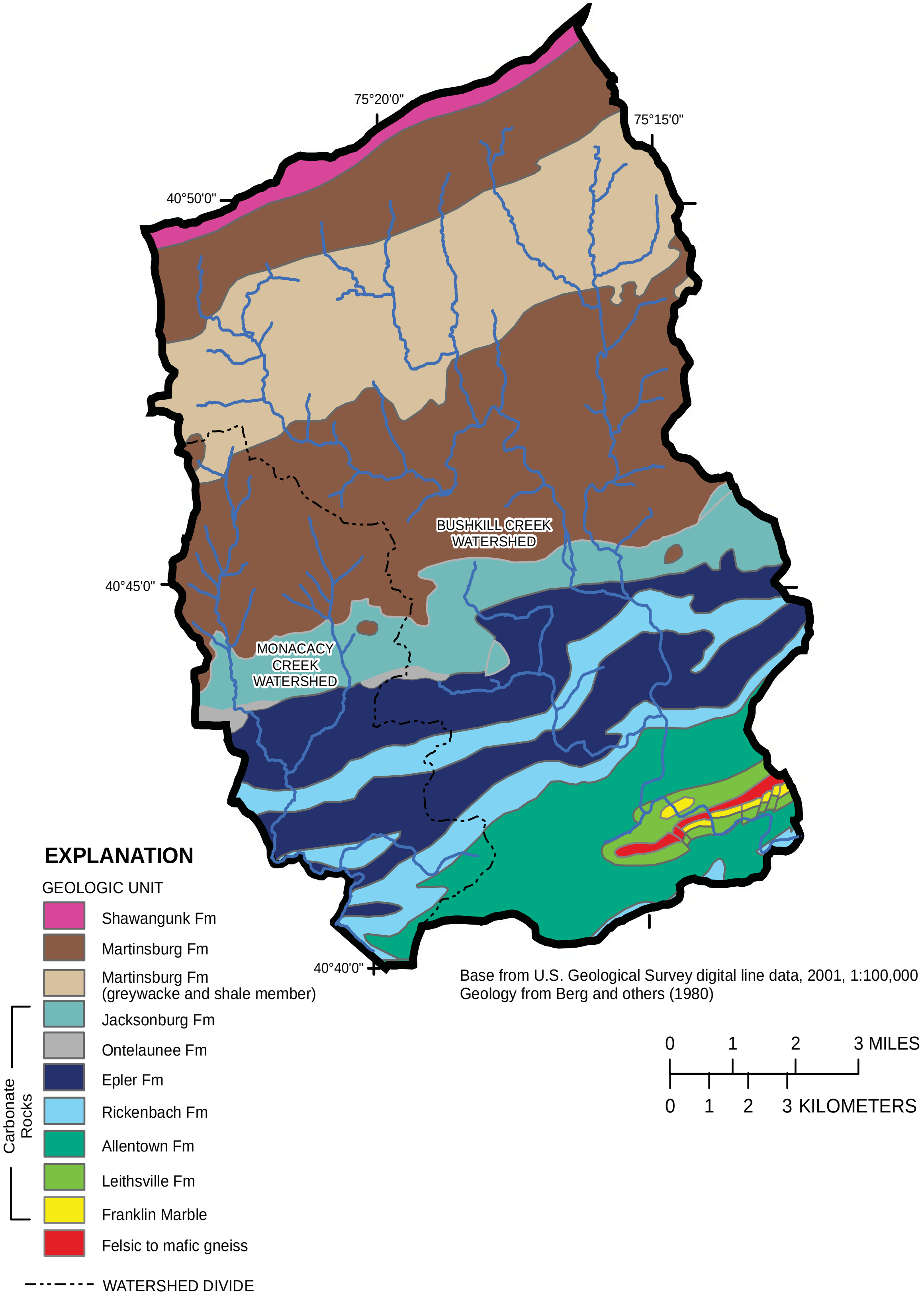
Hydrogeologic Setting

The study area is 101 mi^2 and includes Bushkill Creek watershed and the eastern part of Monocacy Creek watershed in Northampton County, Pa. (fig. 1). The study area is almost entirely in the Great Valley Section of the Ridge and Valley Physiographic Province in Pennsylvania and is underlain by Paleozoic bedrock covered with remnants of pre-Wisconsinan glacial drift. The oldest rocks are gneisses of Precambrian age within the Reading Prong Section of the New England Physiographic Province that crop out in the southern part of the study area. The remainder of the southern part of the study area is characterized by karst terrain of low relief developed on carbonate rocks—Franklin Marble of Precambrian age; Leithsville and Allentown Formations of Cambrian age; and Rickenbach, Epler, Ontelaunee, and Jacksonburg Formations of Ordovician age (fig. 2). The northern part of the study area is underlain by noncarbonate rocks—slate, siltstone, and greywacke of the Martinsburg Formation of Ordovician age and conglomeratic sandstone of the Shawangunk Formation of Silurian age.

Ground water in the study area is recharged by infiltration of local precipitation and streamflow. Ground water flows predominantly through secondary openings in the bedrock and discharges to springs, streams, quarries, and wells. Because direct runoff from the karst topography is minimal, ground-water recharge to areas underlain by carbonate rocks is probably greater than to areas underlain by noncarbonate rocks. In addition, streams draining the noncarbonate-rock uplands lose water in some reaches as they cross the carbonate rocks. The major ground-water uses in the basin are associated with the mining industry (Thomas Denslinger, Pennsylvania Department of Environmental Protection, written commun., 2005).

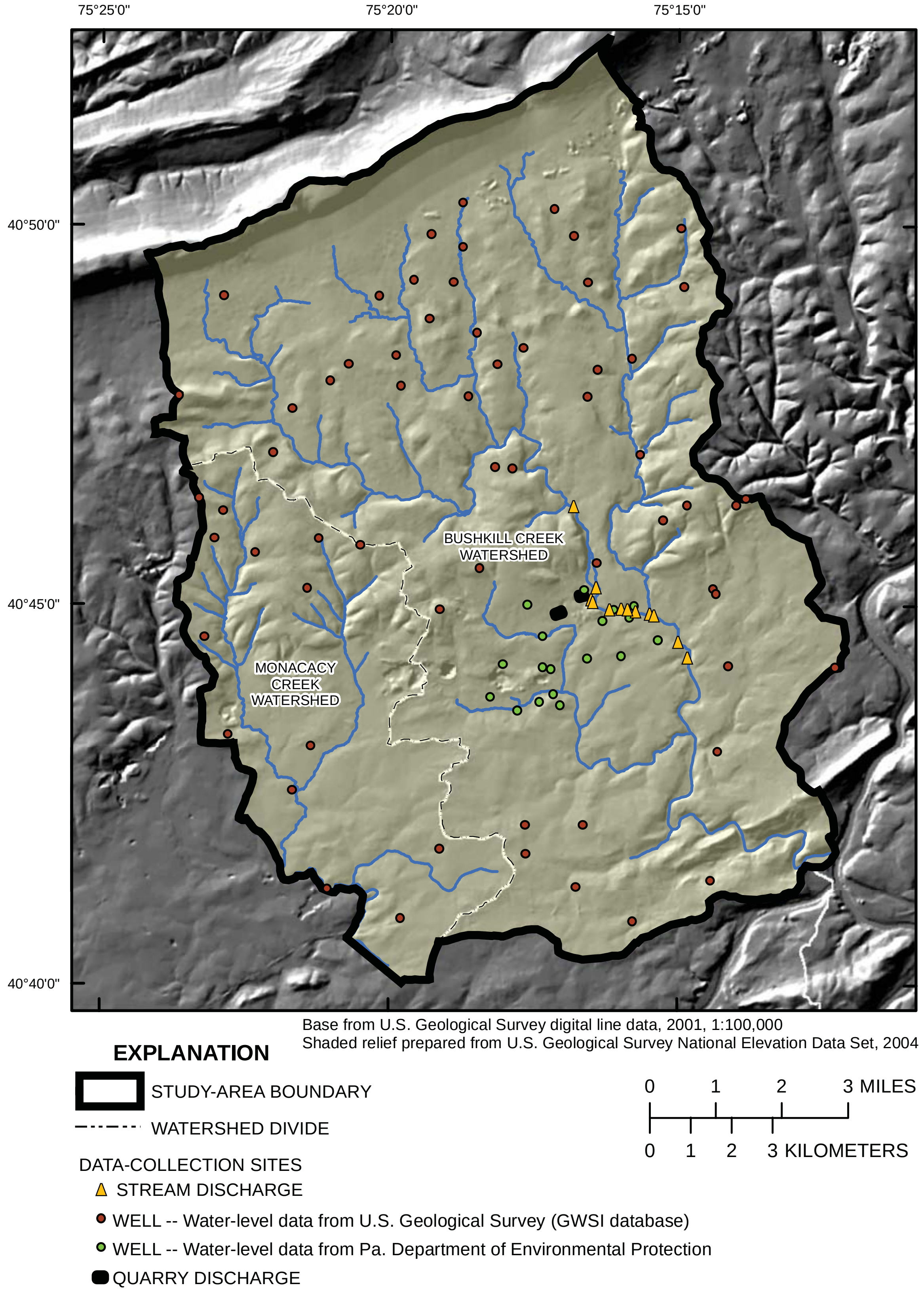
Available Data

For this preliminary study, only water-level measurements and discharge data that could be readily accessed from electronic data sets were used. Data were obtained from the USGS Ground Water Site Inventory (GWSI) database and the PaDEP Pottsville Mining Office. Locations of available stream, well, and quarry discharge data are shown in figure 3.



Base from U.S. Geological Survey digital line data, 2001, 1:100,000
Geology from Berg and others (1980)

Figure 2. Bedrock geology of the study area in Bushkill and parts of Monocacy Creek watersheds, Northampton County, Pennsylvania.



Base from U.S. Geological Survey digital line data, 2001, 1:100,000
Shaded relief prepared from U.S. Geological Survey National Elevation Data Set, 2004

Figure 3. Locations of available water-level and discharge data used to adjust the ground-water flow model of Bushkill and parts of Monocacy Creek watersheds, Northampton County, Pennsylvania.

Water-Level Measurements

Available water-level measurements from GWSI and PaDEP are listed in table 1. The water levels in the GWSI database were from 60 wells measured for various studies during1930-2001, so the water levels represent differing hydrologic conditions. Because of the variable time periods of the measurements and because the well altitudes were not surveyed, the water levels were considered to represent average, steady-state ground-water levels to about +/- 30 ft of the true value. This error estimate is based on the accuracy of well altitudes derived from 7.5-minute topographic maps (+/- 5 to 10 ft) and on the range of typical seasonal water-levels fluctuations (+/- 5 to 30 ft).

Periodic water-level measurements from 18 observation wells were obtained from PaDEP (fig. 3). The water levels were measured by quarry operators or PaDEP personnel. The mean water level from November 2004 through June 2005 was computed for each well and used as a calibration target for average, steady-state conditions (table 1). The well altitudes were surveyed, so the water-level altitudes should be accurate to less than +/- 1 ft.

Discharge Measurements

Discharge measurements from a quarry and in Bushkill Creek were used for model adjustment (fig. 3). Pumping from a large quarry near Bushkill Creek averaged about 77 ft^3/s during 2005 (Sharon Hill, Pennsylvania Department of Environmental Protection, written commun., 2005). It was assumed the average pumping rate approximated the average, steady-state rate of ground-water inflow to the quarry. However, it is possible the rate of ground-water inflow was less than the pumping rate if surface water, which was lost via seepage through the streambed of nearby creeks, moved into the quarry in conduits above the water table. For these preliminary simulations, all stream losses were assumed to reach the water table.

Streamflow was measured at 12 sites in Bushkill and Little Bushkill Creeks during a seepage study by PaDEP on July 21-22, 2005 (table 2 and fig. 4). Gains and losses of base flow between sites were computed and used to adjust the model. Because the measurements were conducted during low flow, they needed to be scaled to represent average, steady-state hydrologic conditions. The scale factor was determined as the ratio of the average base flow of 60 ft^3/s during 1967-2005 at that station determined from hydrograph separation with the computer program PART (Risser and others, 2005, p. 18) to the streamflow of 12 ft^3/s measured at the streamflow-gaging station 01451800 Jordan Creek near Schnecksville on July 21, 2005. The scale factor of 5 was assumed to represent the ratio of average base flow to streamflow measured on July 21, 2005, for streams draining the Martinsburg Formation. Therefore, gains in measured streamflow between stations in parts of the basin underlain mostly by the Martinsburg Formation were multiplied by 5 to represent average, steady-state conditions. This scaling was applied to streamflow measurements at sites 0, 1, and 7.5 (table 2). For losing reaches, the measured losses were not scaled, because it was not known if the losses would increase or decrease during wetter, average hydrologic conditions. This scaling procedure provided an approximation of average annual base flow for these preliminary simulations, but additional streamflow measurements would be needed at higher flows to provide better data for model adjustments.

Table 1. Water levels in wells used to adjust the ground-water flow model of Bushkill and parts of Monocacy Creek watersheds, Northampton County, Pennsylvania.

[USGS, U.S. Geological Survey; PaDEP, Pennsylvania Department of Environmental Protection; NGVD 29; National Geodetic Vertical Datum of 1929]

Well identifier	Data source	Water-level altitude, in feet above NGVD 29
NP-56	USGS	298
NP-57	USGS	232
NP-101	USGS	745
NP-102	USGS	627
NP-109	USGS	708
NP-115	USGS	685
NP-127	USGS	650
NP-268	USGS	656
NP-270	USGS	603
NP-335	USGS	680
NP-336	USGS	662
NP-341	USGS	735
NP-342	USGS	680
NP-346	USGS	667
NP-348	USGS	656
NP-349	USGS	655
NP-350	USGS	632
NP-351	USGS	673
NP-353	USGS	700
NP-354	USGS	575
NP-359	USGS	480
NP-363	USGS	550
NP-364	USGS	610
NP-365	USGS	620
NP-367	USGS	555
NP-368	USGS	670
NP-369	USGS	640
NP-371	USGS	700
NP-373	USGS	710
NP-374	USGS	669
NP-377	USGS	662
NP-380	USGS	580
NP-381	USGS	420
NP-382	USGS	603
NP-385	USGS	554
NP-386	USGS	573
NP-390	USGS	650
NP-391	USGS	658
NP-400	USGS	790
NP-420	USGS	855
NP-442	USGS	695
NP-443	USGS	640
NP-490	USGS	632
NP-581	USGS	340
NP-624	USGS	292
NP-629	USGS	267
NP-631	USGS	312
NP-633	USGS	230
NP-641	USGS	294
NP-642	USGS	325
NP-646	USGS	363
NP-647	USGS	348
NP-662	USGS	372
NP-674	USGS	345
NP-677	USGS	638
NP-687	USGS	286
NP-741	USGS	295
NP-760	USGS	321
NP-771	USGS	385
NP-806	USGS	336
NP-816	USGS	788
NP-820	USGS	536
DEP1	PaDEP	300.9
DEP2	PaDEP	292.3
DEP3	PaDEP	279.9
DEP4	PaDEP	235.9
DEP5	PaDEP	309.1
DEP6	PaDEP	285.1
EI-MW4	PaDEP	341.2
EI-MW5	PaDEP	[1]442.9
EI-MW6	PaDEP	270.7
EI-MW7	PaDEP	277.2
EI-MW8	PaDEP	307.4
Es-MW-5	PaDEP	293.3
Es-MW-6	PaDEP	293.3
Es-MW-7	PaDEP	313.6
H-MW-1	PaDEP	306.8
H-MW-2	PaDEP	361.9
H-MW-3	PaDEP	311.4
H-MW-4	PaDEP	313.6

[1] Used in model calibration, but value was later found to be in error.

Table 2. Measurements of streamflow and quarry discharge used to adjust the ground-water flow model of Bushkill and parts of Monocacy Creek watersheds, Northampton County, Pennsylvania.

[Measurements made by Pennsylvania Department of Environmental Protection (PaDEP) during a seepage study on July 21-22, 2005}

Site identifier (locations shown on figure 4)	Measured streamflow, in cubic feet per second	Measured gain (+) or loss (-), in cubic feet per second	Scaled gain (+) or loss (-) used as calibration target for ground-water flow model, in cubic feet per second	Scaled streamflow, in cubic feet per second	Notes
0	6.0	6.0	30.0	30.0	1,2
1	6.2	0.2	1.0	31.0	2
1.5	0.4	-5.8	-5.8	25.2	
2	48.4	48.0	77.0	102.2	3
4	51.0	2.6	2.6	104.8	4
5	48.1	-2.9	-2.9	101.9	
6	30.6	-17.5	-17.5	84.4	
7	13.8	-16.8	-16.8	67.6	
7.5 (tributary)	3.6	3.6	18.0	18.0	1, 2, 5
8	15.8	-1.6	-1.6	84.0	6
9	7.1	-8.7	-8.7	75.3	
10	5.4	-1.7	-1.7	73.6	

[1] Measured streamflow at this site was assumed to represent the net gain for all reaches upstream of measurement site.

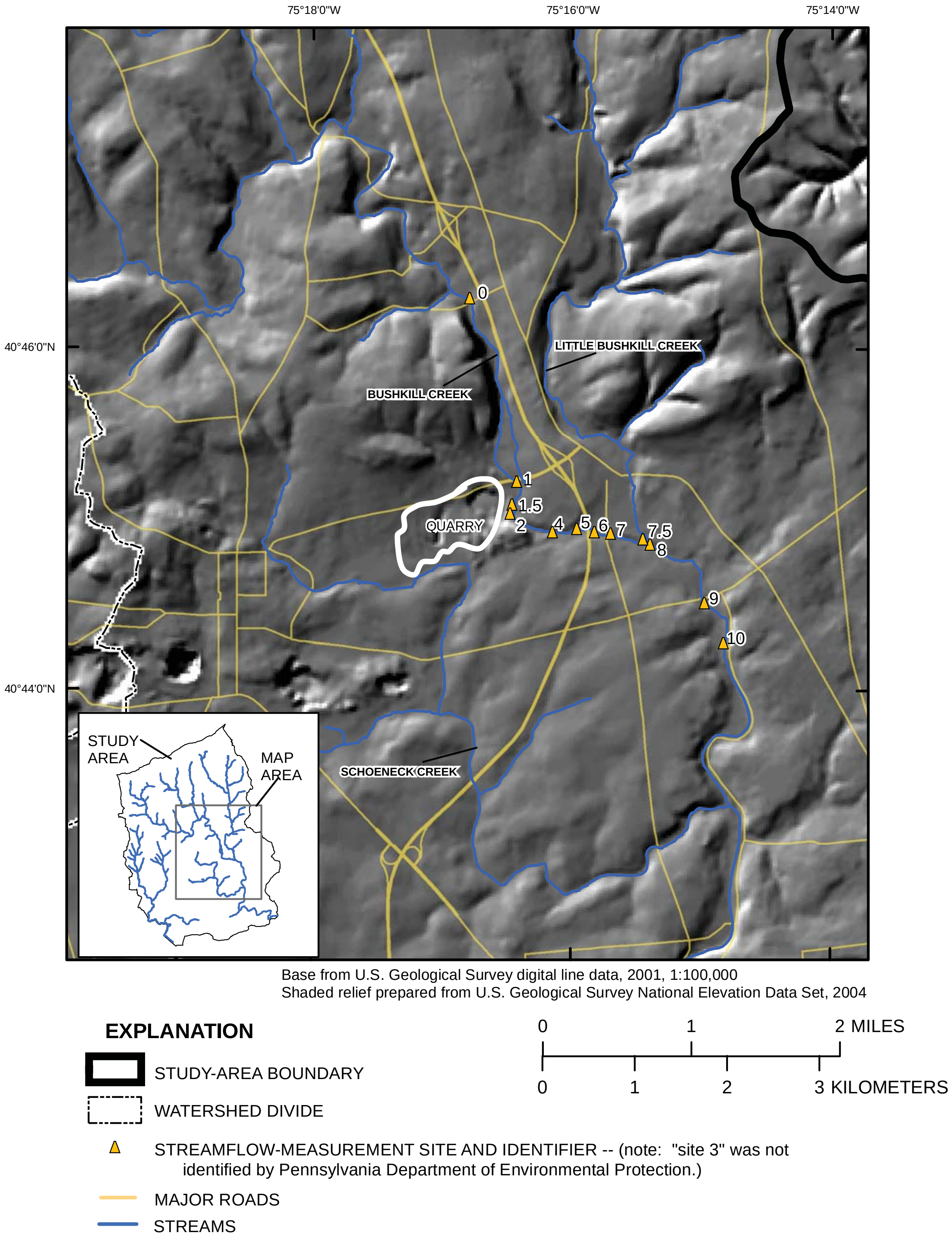
[2] Streamflow gains at sites 0, 1, and 7.5 were scaled by a factor of 5 to represent average steady-state conditions as a calibration target for the model. The scaling factor is the ratio of average base flow during 1967-2005 (60 cubic feet per second) at that station determined by hydrograph separation to the streamflow measured at the streamflow-gaging station 01451800 Jordan Creek near Schnecksville on July 21, 2005 (12 cubic feet per second).

[3] Streamflow gain at site 2 was entirely caused by water discharged from a quarry. During the period of streamflow measurements, quarry discharge was reduced to 48 cubic feet per second, but average discharge during 2005 was about 77 cubic feet per second. Therefore, the gain between stations 1.5 and 2 was increased to 77 cubic feet per second to represent average, steady-state conditions.

[4] There was not a site identified as “site 3" in the PaDEP seepage study.

[5] Site 7.5 is on Little Bushkill Creek, a tributary to Bushkill Creek between sites 7 and 8. (Identified as site 8.5 by PaDEP).

[6] Base-flow loss between sites 7 and 8 was computed as the flow measured at site 8 minus the sum of flow measured at sites 7 and 7.5.



Base from U.S. Geological Survey digital line data, 2001, 1:100,000
Shaded relief prepared from U.S. Geological Survey National Elevation Data Set, 2004

Figure 4. Sites on Bushkill Creek where streamflow was measured by Pennsylvania Department of Environmental Protection on July 21-22, 2005.

Simulated Water Budgets and Ground-Water/Surface-Water Interactions

A ground-water flow model was used to simulate the ground-water/surface-water interactions in Bushkill and parts of Monocacy Creek watersheds. The numerical model was based on a simplified conceptual model of the hydrogeologic system, which can be refined iteratively through evaluation of modeling results and additional data collection.

Conceptual Model

A simplified conceptual model of steady-state recharge, movement, and discharge of ground water was used to guide development of the numerical ground-water flow model of the study area. The ground-water system was conceptualized as a water-table aquifer recharged by uniform infiltration of precipitation and seepage of streamflow in losing stream reaches. Ground water was viewed as moving through secondary openings (fractures or karst features) in the bedrock until discharging to streams or a quarry.

The complex geologic structure and various geologic units in the study area were conceptualized as homogeneous, anisotropic units with vertical contacts between units. At the most basic level, the hydrogeologic framework was conceptualized as an upland area underlain by noncarbonate rocks and a lowland area underlain by carbonate rocks. Enlargement of secondary openings in the carbonate rocks by dissolution has created a heterogeneous aquifer capable of transmitting large quantities of ground water while, at the same time, yielding very small quantities of water to some wells. For purposes of this study, the upland and lowland areas were conceptualized as having a sufficient density of secondary openings to approximate a porous medium at the scale of the investigation. For the study area underlain by carbonate rocks, this assumption is questionable but was used for this preliminary investigation. In one location near Bushkill Creek, a zone of high transmissivity has been hypothesized as a possible conduit (Hazlett-Kincaid, Inc., 2002, p. 4 and fig. 3; Richard R. Parizek, Consulting Hydrogeologist, written commun., 2006). This one zone was explicitly conceptualized as a probable pathway for large volumes of ground-water flow in this study, but other highly transmissive fractures and conduits are likely in the area.

Ground-water discharge was simplified in the conceptual model by considering only discharge to streams and a single quarry. Some ground water also discharges to wells and other quarries and as evapotranspiration along the riparian zone; however, these sinks were not considered in the model.

Model Development

A numerical model was used to simulate 2-dimensional ground-water flow in the study area. Simulations were conducted under steady-state conditions, which represent the ground-water/surface-water relations for conditions of average annual ground-water recharge and discharge. Changes caused by seasonal variations in recharge or pumping were not simulated.

Computer Code and Grid

The finite-difference computer code MODFLOW-2000 (Harbaugh and others, 2000) was used with the particle-tracking program MODPATH (Pollock, 1994) to simulate 2-dimensional ground-water flow and display results. A graphical user interface linked to Argus Numerical Environments was used for pre- and post-processing of data (Winston, 2000).

The study area was divided into a finite-difference grid (fig. 5) with 1 layer, 138 rows, and 135 columns. The horizontal dimensions of the cells were varied so that small cells were in the vicinity of a major losing reach of Bushkill Creek and a quarry, where ground-water gradients were expected to be large. The smallest cells were 164[1] by 164 ft and the largest were 656 by 656 ft in horizontal dimension. The model grid was constructed with rows oriented N. 70° E. to align with the general strike of geologic units in the area as shown in figure 2. The orientation of model rows along strike was important because the carbonate rocks have been conceptualized as anisotropic, with the principal direction of horizontal hydraulic conductivity along the strike of units (Richard R. Parizek, Consulting Hydrogeologist, written commun., 2006).

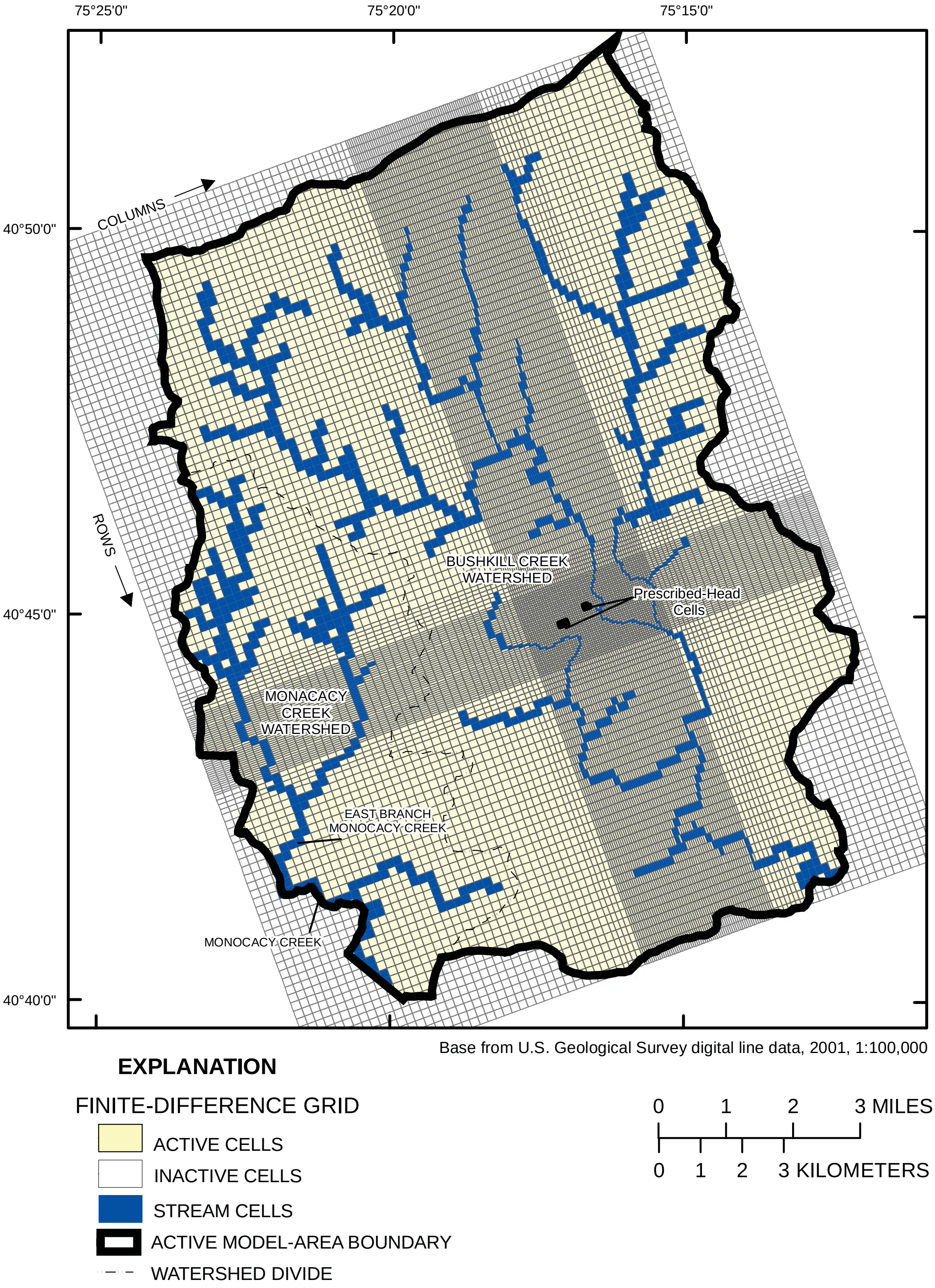
Boundary Conditions

The altitude of the top of each model cell was set equal to the altitude of land surface from the USGS 30-m digital elevation model (DEM). The thickness of all cells was 656 ft, which was achieved by setting the no-flow boundary at the bottom of each cell equal to the land-surface altitude minus 656 ft. The bottom of the model was based on the assumed depth below which very little ground-water movement occurs. Although the depth of active flow is not well known, in adjacent Lehigh County, nearly all water-bearing zones were encountered at depths less than 400 ft below land surface in the Martinsburg Formation, and about 80 percent of water-bearing zones in carbonate rocks were encountered at depths less than 650 ft (Wood and others, 1972).

The extent of the modeled area was defined with no-flow cells along the topographic divide of Bushkill Creek watershed except where adjacent to the Monocacy Creek watershed. In

---

[1] The model was constructed in length units of meters, which are reported in feet for this report, resulting in values that may seem unusual or may convey more precision than warranted.



Base from U.S. Geological Survey digital line data, 2001, 1:100,000

Figure 5. Finite-difference grid and location of stream cells and prescribed-head cells for the ground-water flow model of Bushkill and parts of Monocacy Creek watersheds, Northampton County, Pennsylvania.

that area, the no-flow boundary was extended to the west of East Branch Monocacy Creek and of one unnamed tributary to the main stem of Monocacy Creek, so the divide between the Bushkill and Monocacy ground-water basins would not be predetermined. This boundary lies along the western divide of East Branch Monocacy Creek watershed or along the main stem of Monocacy Creek. The location of no-flow cells along the topographic divide of Bushkill Creek watershed may not be ideal along the eastern boundary of the modeled area underlain by carbonate rocks (fig. 2), because, as with the boundary between the Bushkill and Monocacy ground-water basins, it is not known if the ground-water and topographic basins are coincident. The effect of this boundary could be tested by moving it further to the east, but such testing was not conducted for this preliminary study.

Recharge from Precipitation

Recharge from precipitation was simulated as a prescribed flux of 15 in/yr uniformly across the top of each cell. This rate was used because it was within the range of base-flow and recharge estimates determined by use of streamflow-hydrograph methods PART and RORA (Risser and others, 2005, p. 18) for USGS streamflow-gaging stations on Monocacy and Jordan Creeks (fig. 1). As noted earlier, recharge was probably greater in areas underlain by carbonate bedrock than areas underlain by noncarbonate bedrock, but for this preliminary modeling, its value was not varied spatially.

Streams

Streams were simulated by use of the STR package in MODFLOW-2000 (Prudic, 1989), which allows streams to gain or lose water and accounts for the flow in each stream cell so that losses cannot exceed the simulated streamflow. The stream stage was set equal to the altitude of land surface from the USGS 10-m DEM. Top of the streambed was assumed to be 3.28 ft below the stream stage, and bottom of the streambed was 6.56 ft below the stream stage. Stream width was simulated as 3.28 ft for all stream cells. These stream dimensions were not representative of the real streams channels but were used for convenience in these preliminary simulations.

Hydraulic conductivity of the streambed was assigned an initial value of 3.28 ft/d, based on the assumption of a good hydraulic connection between stream and aquifer. The hydraulic conductivity of the streambed was adjusted (see discussion on Model Adjustments) for Bushkill Creek in the area where streamflow gains and losses were measured.

Quarry

Where extraction of mineral resources extends below the water table, withdrawals of ground water may be required to operate a quarry or mine. Only one mining operation in the Bushkill Creek watershed was pumping in 2005 to dewater the quarry pit (Roger Hornberger, Pennsylvania Department of Environmental Protection, oral commun., 2005). Average pumping from the quarry was about 77 ft^3/s in 2005, which was the largest withdrawal of water in the study area. It was also reportedly the largest discharge of water from any quarry in Pennsylvania (Roger Hornberger, Pennsylvania Department of Environmental Protection, oral commun., 2006). The water was discharged into Bushkill Creek.

In the model, ground-water flow into the quarry was simulated with two prescribed-head cells representing the altitude of ground water in two sumps (fig. 5). The altitudes of the prescribed heads were set to 147 and 220 ft (about 200 and 130 ft below land surface), which represented the approximate altitudes of water in the two sumps. The discharge of water from the quarry was simulated by adding a flow of 77 ft^3/s to the appropriate stream reach of Bushkill Creek adjacent to the quarry.

Wells

Although ground water was extracted by wells within the study area, the quantity of the withdrawal was minor compared to that withdrawn by the quarry. Thus, for the preliminary simulations, ground-water withdrawals from wells were not included in the model.

Aquifer Properties

Initial estimates of aquifer properties used in the model were based on the generalization that the carbonate rocks have a higher hydraulic conductivity than the noncarbonate rocks; the values were subsequently changed during the model-adjustment procedure. Thus, a hydraulic conductivity along model rows (along strike of geologic units) was initially assigned as 10 ft/d for all carbonate rocks and 0.3 ft/d for all noncarbonate rocks. The hydraulic conductivity along model columns was assigned as 2 ft/d for all carbonate rocks; noncarbonate rocks were assumed to be isotropic.

Model Adjustments

Model adjustment is a process in which aquifer properties are changed until the simulated response of the model mimics the measured response in the real physical system. Aquifer properties and recharge in the model were adjusted by use of the parameter-estimation program that is integrated into MODFLOW-2000 (Hill and others, 2000) and by trial-and-error. Water-level and streamflow data available in electronic databases from USGS and PaDEP were used to adjust the properties for this preliminary model. Additional historical data from other sources and data from new field studies could be incorporated to refine values of aquifer properties.

Values of recharge, hydraulic conductivity, horizontal anisotropy, and streambed hydraulic conductivity in the model were adjusted by trying to match measurements of (1) water levels in 60 wells available from the USGS GWSI database,

(2) water levels in 18 observation wells provided by PaDEP, (3) ground-water inflow to a quarry, and (4) gains and losses of stream base flow in a reach of Bushkill Creek (fig. 3).

Weighting of Measurements

In the parameter-estimation program, residuals (difference between observed and simulated values) in streamflow and quarry discharge were multiplied by a weighting factor, primarily to convert discharge rates to the same units as water-level measurements. The value of the weighting factor was chosen so that the sum of weighted residuals for the streamflow and quarry-discharge measurements would be about the same magnitude as for the sum of weighted residuals for water-level data from wells. Streamflow and quarry-discharge residuals were each multiplied by 0.0058 ft/(ft^3/s).

For preliminary model simulations, none of the water-level measurements were weighted (weighting factor=1). Water-level measurements provided by PaDEP should be given a greater weight relative to those from the USGS GWSI because PaDEP measurements were more accurate. This is a limitation of the preliminary work that could affect estimates of hydraulic parameters.

Adjusted Model Parameters

Nine parameters were used to represent hydrologic properties in MODFLOW-2000. Seven parameters were used to estimate the hydraulic conductivity of 12 geologic units and a hypothesized fracture zone with large transmissivity (table 3). The horizontal anisotropy of the carbonate rocks was represented by a parameter (hani_carb) and recharge was defined by a parameter (rech). Each parameter was either assigned a value or it was optimized by the parameter-estimation process in MODFLOW-2000. Model adjustments focused on parameters that, when changed, caused the greatest proportional change in simulated water levels and flow, which were indicated by their composite scaled sensitivities (fig. 6). Values for K(carb), K(fract), and K(jack) were optimized by MODFLOW-2000, and the other parameters were assigned values based on trial-and-error adjustment.

Table 3. Parameters used to represent hydraulic conductivity in the ground-water flow model of Bushkill Creek and part of Monocacy Creek watersheds, Northampton County, Pennsylvania.

[ft/d, foot per day]

Parameter name	Geologic unit	Age	Lithology	Adjusted value of hydraulic conductivity along strike of geologic units, along model rows (ft/d)
		Noncarbonate rocks		
K(sil)	Shawangunk Formation	Silurian	Sandstone	0.14
	Martinsburg Formation (southern part)	Ordovician	Slate and shale	
	Granitic gneiss	Precambrian	Granitic gneiss	
K(martins)	Martinsburg Formation (northern part)	Ordovician	Slate and shale	1.8
K(grey)	Martinsburg Formation	Ordovician	Slate and greywacke	.62
		Carbonate rocks		
K(jack)	Jacksonburg Formation	Ordovician	Shaley limestone	8.8
K(carb)	Ontelaunee Formation	Ordovician	Dolomite	61
	Epler Formation	Ordovician	Limestone and dolomite	
	Rickenbach Formation	Ordovician	Dolomite	
	Allentown Formation	Cambrian	Dolomite	
K(fract)	Hypothesized highly fractured zone in Epler and Jacksonburg Formations	Ordovician	Limestone and dolomite	1,013
K(prong_carb)	Leithsville Formation	Cambrian	Dolomite	13
	Franklin Marble	Precambrian	Marble	

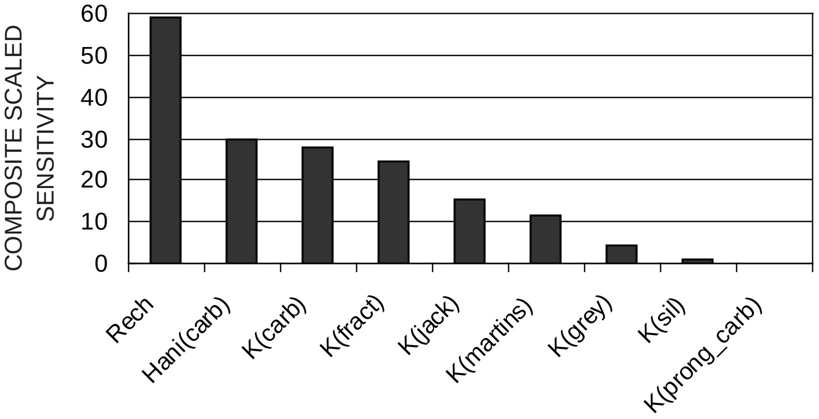


Figure 6. Composite scaled sensitivity of hydraulic parameters used in the ground-water flow model of Bushkill and parts of Monocacy Creek watersheds, Northampton County, Pennsylvania. (See table 3 for definitions of parameters)

The adjusted values of hydraulic conductivity used in the model are shown in table 3. The value of horizontal anisotropy (ratio of hydraulic conductivity along strike of geologic units to along dip) for carbonate rocks was set to 6:1 to represent the concept of preferential ground-water flow parallel to strike of geologic units. The recharge rate was predetermined as 15 in/yr by adjusting the calibration targets of stream base flow at sites 0, 1, and 7.5 to discharge at rates corresponding to a recharge of 15 in/yr, as described previously.

Simulated and measured water levels and flows are compared in figure 7. Steady-state ground-water levels simulated by the model were compared to the basinwide GWSI water-level data from 60 wells (fig. 7A) and to water-level data provided by PaDEP from 18 observation wells (fig. 7B). The model simulated the regional differences in ground-water altitude reasonably well, because most simulated water levels were within the estimated accuracy of the measurements (fig. 7A). Use of the basinwide GWSI data in the calibration procedure, even though the water-level altitudes were not known with great accuracy, provided data for the carbonate and noncarbonate rocks, which enabled the model to show that the hydraulic conductivity of the noncarbonate rocks must be on the order of about 10 times less than the effective equivalent isotropic hydraulic conductivity of most of the carbonate rocks. The highly accurate water-level data supplied by PaDEP, however, indicated that the correspondence between simulated and measured water levels was not compelling when viewed at the local scale (fig. 7B), probably because of local heterogeneity of the carbonate rocks. This suggests the model should be used with caution at the local scale.

Ground-water inflow to a quarry of 74 ft^3/s was simulated by the model compared to the measured discharge of 77 ft^3/s (fig. 7C). To simulate the inflow, the model indicated the hydraulic conductivity of the carbonate rocks in the vicinity of the quarry must be large. The hydraulic-conductivity values determined by the parameter-estimation process for the Jacksonburg Limestone and the Epler Formation were 8.8 and 61 ft/d, respectively, along model rows in the direction of the strike of geologic units. In the direction of minimum hydraulic conductivity, across strike, the values were 1.5 and 10 ft/d, respectively. The effective equivalent isotropic hydraulic-conductivity value for the carbonate rocks is the geometric mean of the directional hydraulic-conductivity values (Kruseman and de Ridder, 1990, p. 134). For the Jacksonburg Formation, the geometric mean hydraulic conductivity was about 3.6 ft/d; for the Epler Formation, it was about 25 ft/d. A hydraulic-conductivity value of about 1,000 ft/d was the optimal value determined for the hypothesized highly transmissive fracture zone [K(fract) in table 3].

Gains and losses of stream base flow simulated by the model were compared to measured or scaled gains and losses of base flow from the seepage run of July 21-22, 2005 (fig. 7D). The simulated rate that water is gained or lost in streams was sensitive to the hydraulic conductivity of the streambed and of a hypothesized highly transmissive fracture zone. The losses of streamflow in Bushkill Creek were simulated by adjusting the hydraulic conductivity of the streambed from the initial estimate of 3.28 ft/d to values as small as 0.01 ft/d and as large as 500 ft/d. The small value of hydraulic conductivity was used where the stream channel was known to have been lined with low-permeability materials. In some areas where sinkholes are known to exist in the streambed, the large values of hydraulic conductivity seemed reasonable. In other areas, it is not clear there was a physical basis for such large values. Adjustments of streambed hydraulic conductivity were done by trial-and-error for this preliminary model.

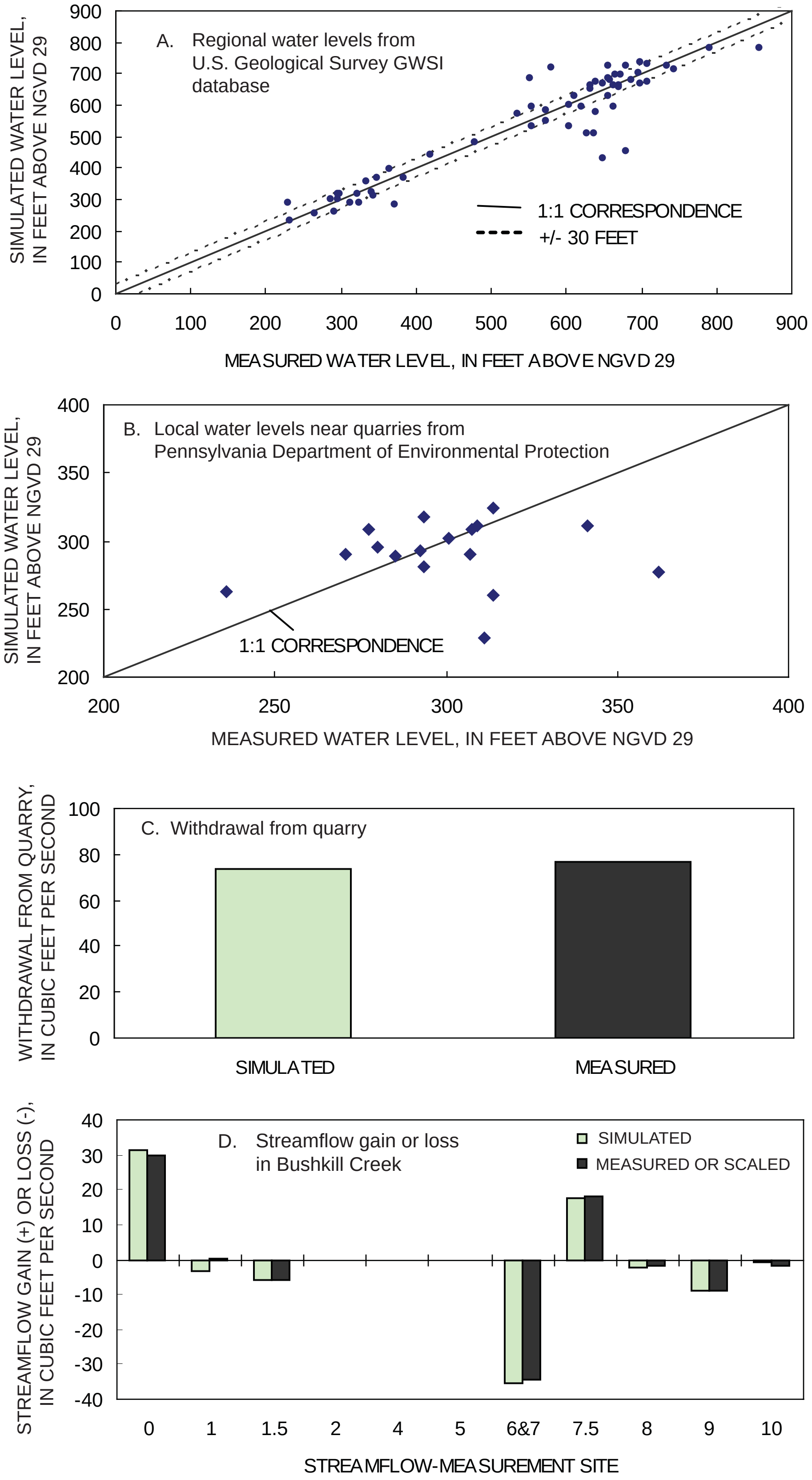


Figure 7. Measured and simulated ground-water levels and base-flow gain or loss simulated by use of the ground-water flow model of Bushkill and parts of Monocacy Creek watersheds, Northampton County, Pennsylvania.

Preliminary Results of Model Simulations

Preliminary results from modeling simulations are described in this section. Simulations were conducted for (1) predevelopment conditions, (2) a water table lowered for quarry operations, and (3) anthropogenic changes in hydraulic conductivity of the streambed and aquifer.

Predevelopment Conditions

Ground-water flow in the study area was simulated under steady-state predevelopment conditions. This was done because hydrologic data were not available that represented conditions predating the alteration of the natural stream channels and ground-water system by railroads, highways, and quarries. The simulated predevelopment water-table surface is shown in figure 8. Water-table gradients were steeper in the northern part of the study area underlain by the Martinsburg Formation, compared to the shallower gradients in the southern part underlain by carbonate rocks. The differences were the result of the low hydraulic conductivity of the Martinsburg Formation relative to the carbonate rocks.

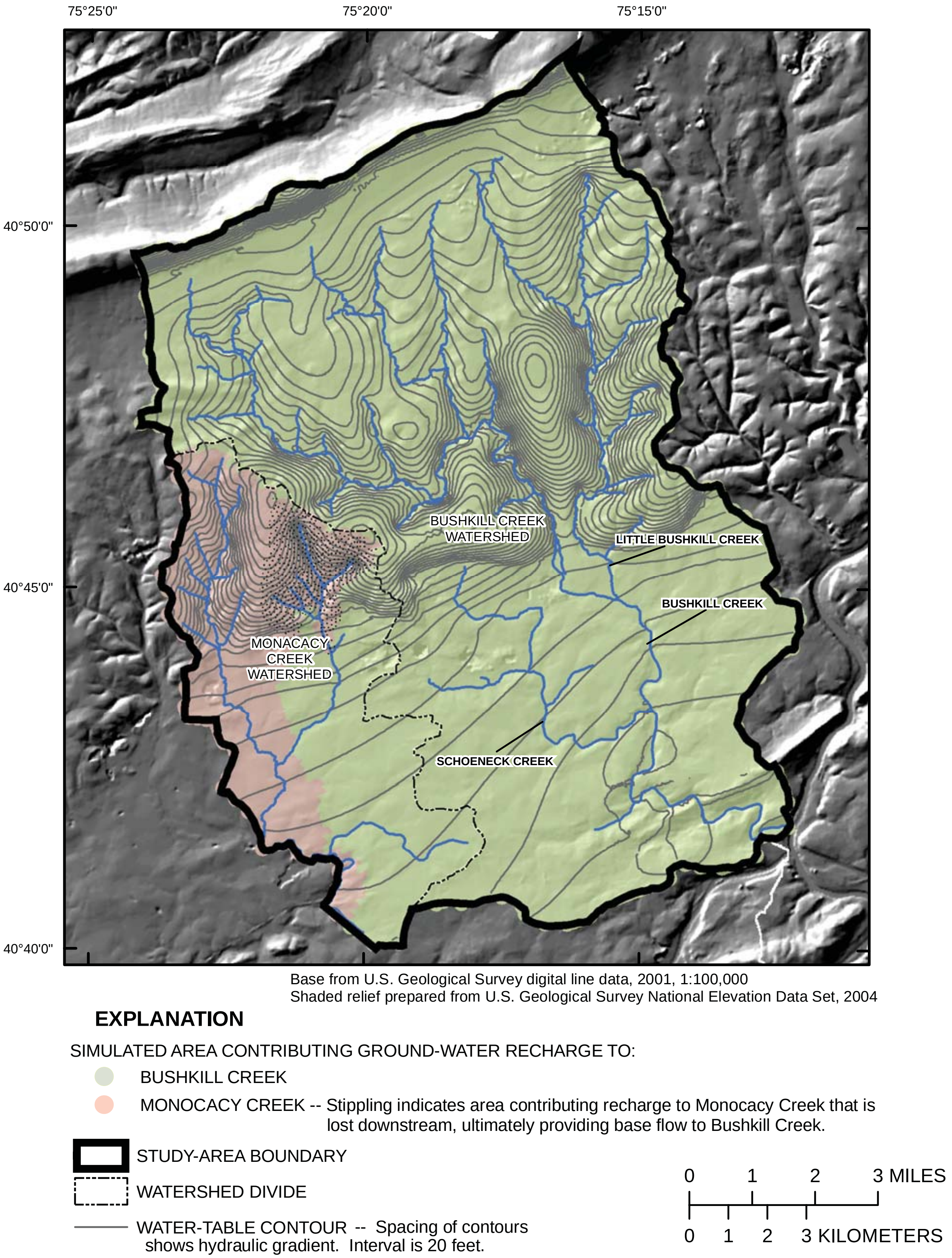
Preliminary model simulations of predevelopment conditions indicated ground-water basin and watershed divides were not coincident in areas underlain by carbonate rocks. The divide between areas contributing ground water to Bushkill and Monocacy Creeks was west of the watershed (topographic) divide between those basins in the area underlain by carbonate rocks (fig. 8). Thus, recharge in the area between those divides ultimately discharged to Bushkill Creek, even though the recharge occurred within the watershed of Monocacy Creek. Recharge was captured from Monocacy Creek watershed because the lower altitude of Bushkill Creek in the southern part of the study area allowed it to be a more effective drain for the ground-water system. The anisotropy of the carbonate rocks added to the ability of Bushkill Creek to capture recharge from the Monocacy Creek watershed. By simulating the hydraulic conductivity of the carbonate rocks as six times greater along the strike of geologic units (about N. 70° E.), the ability of Bushkill Creek to capture recharge was enhanced parallel to strike. About 14 percent of the total inflow for the simulated ground-water budget for Bushkill Creek was captured from Monocacy Creek watershed (10 percent from precipitation and 4 percent from stream leakage) (table 4).

The stream reaches simulated as gaining (receiving ground-water discharge) for average, steady-state predevelopment conditions are shown in figure 9. Reaches not indicated as gaining were either losing reaches, where streamflow was lost as infiltration through the streambed, or were dry. Schoeneck Creek, a tributary to Bushkill Creek, was simulated as dry throughout almost its entire reach because the simulated altitude of the water table was below the altitude of the streambed. On Monocacy Creek, several sections were simulated as losing or dry reaches for average, steady-state conditions.

Because streamflow losses were simulated from Monocacy Creek within the area contributing recharge to Bushkill Creek, the total source area for water that ultimately discharged as ground-water flow into Bushkill Creek was larger than just the area contributing ground-water recharge shown in figure 8 (green shading). The total area providing water to the quarry included the watershed of the easternmost tributary of Monocacy Creek. This additional area shown with a stippled pattern in figure 8 provided streamflow that was lost within the area contributing recharge.

Table 4. Simulated ground-water budget for Bushkill Creek watershed, Northampton County, Pennsylvania, for predevelopment conditions.

Source of inflow	Rate, cubic feet per second	Percent of total inflow
Recharge from precipitation on Bushkill Creek watershed	88	86.3
Recharge from precipitation captured from Monocacy Creek watershed	10	9.8
Streamflow leakage captured from Monocacy Creek watershed	4	3.9
Total inflow	102	100
Source of outflow	**Rate, cubic feet per second**	**Percent of total outflow**
Discharge to streams in Bushkill Creek watershed	102	100
Total outflow	102	100



Base from U.S. Geological Survey digital line data, 2001, 1:100,000
Shaded relief prepared from U.S. Geological Survey National Elevation Data Set, 2004

EXPLANATION

SIMULATED AREA CONTRIBUTING GROUND-WATER RECHARGE TO:

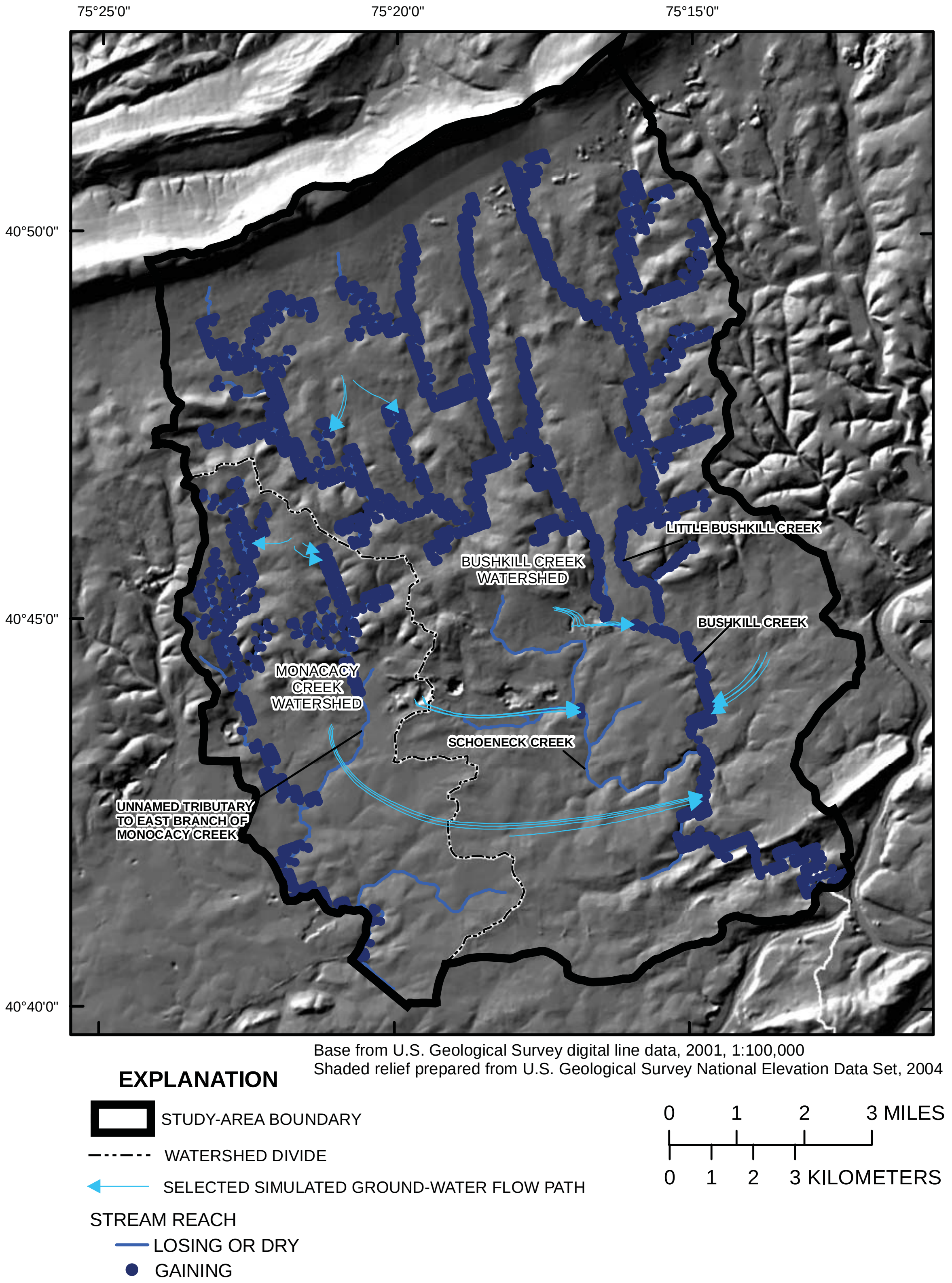
- ● BUSHKILL CREEK
- ● MONOCACY CREEK -- Stippling indicates area contributing recharge to Monocacy Creek that is lost downstream, ultimately providing base flow to Bushkill Creek.

▭ STUDY-AREA BOUNDARY

⬚ WATERSHED DIVIDE

— WATER-TABLE CONTOUR -- Spacing of contours shows hydraulic gradient. Interval is 20 feet.

Figure 8. Simulated predevelopment water table and areas contributing ground water to Bushkill and parts of Monocacy Creek watersheds, Northampton County, Pennsylvania.



Base from U.S. Geological Survey digital line data, 2001, 1:100,000
Shaded relief prepared from U.S. Geological Survey National Elevation Data Set, 2004

Figure 9. Simulated gaining and losing stream reaches and selected ground-water flow paths for predevelopment conditions in Bushkill and parts of Monocacy Creek watersheds, Northampton County, Pennsylvania.

Effects of a Water Table Lowered for Quarry Operations

The basin was simulated under steady-state conditions with the water table prescribed at altitudes of 147 and 220 ft to simulate water levels in two quarry sumps near Bushkill Creek. These were the conditions under which the model was calibrated as described in the section “Model Adjustments.” The simulations indicated that, when compared to predevelopment conditions, the lowered steady-state water table at the quarry had an effect on regional ground-water levels, ground-water divides, and the location of gaining stream reaches.

The simulated change in regional ground-water levels from predevelopment conditions caused by lowering the water table for quarry operation is shown qualitatively in figure 10. The largest decline was centered near where the water-table altitude was held constant at an altitude of 147 ft to simulate the water level at the deepest quarry sump. The area of influence was elongated because of the contrast in hydraulic conductivity between the carbonate and noncarbonate rocks and because the hydraulic conductivity was simulated as six times greater along the strike of geologic units (N. 70˚ E.) compared to across strike. The influence of the ground-water withdrawal extended to the physical boundaries of the model at steady state, but figure 10 shows only the area with a simulated water-level decline of 20 ft or more. The decline in water table was less to the east because infiltration of water from Bushkill Creek was induced by the lowered ground-water levels beneath the creek.

The areas contributing ground-water recharge to gaining streams and the quarry are shown in figure 11. The simulated area contributing recharge was about 14 mi^2 and elongated. Recharge from precipitation and any infiltration of streamflow in this area was diverted to the quarry. Comparison of stream reaches near the confluence of Bushkill and Little Bushkill Creeks in figure 11 to those same reaches in figure 9 shows part of the stream reach changed from gaining to losing. The simulated water budget for Bushkill Creek watershed with prescribed heads at altitudes of 147 and 220 ft to operate a quarry is shown in table 5. Compared to the budget for predevelopment conditions (table 4), the major differences were the quarry discharge, accounting for 46 percent of the outflow, and the leakage of flow from streams in the Bushkill Creek watershed, accounting for 34 percent of the inflow to the ground-water system. Addition of the quarry increased the capture of precipitation and streamflow leakage from the Monocacy Creek watershed by 2 and 3 ft^3/s, respectively (compare values in tables 4 and 5).

The simulated ground-water withdrawal from the quarry (74 ft^3/s) was balanced by an increase of induced infiltration from streams of 55 ft^3/s, a decrease in ground-water discharge to streams of 14 ft^3/s, and an increase of net inflow from Monocacy Creek watershed of about 5 ft^3/s. Some of the recharge to ground water flowing to Bushkill Creek upstream of the quarry discharged to the quarry by streamflow infiltration. This additional area shown with a stippled pattern in figure 11 provided streamflow that was lost within the area contributing recharge.

Table 5. Simulated ground-water budget for Bushkill Creek watershed, Northampton County, Pennsylvania, with the water table in two sumps held at altitudes of 147 and 220 feet to operate a quarry.

Source of inflow	Rate, cubic feet per second	Percent of total inflow
Recharge from precipitation on Bushkill Creek watershed	88	54.3
Recharge from precipitation captured from Monocacy Creek watershed	12	7.4
Streamflow leakage from Bushkill Creek watershed	55	34.0
Streamflow leakage captured from Monocacy Creek watershed	7	4.3
Total inflow	162	100
Source of outflow	**Rate, cubic feet per second**	**Percent of total outflow**
Discharge to streams in Bushkill Creek watershed	88	54.3
Discharge to quarry	74	45.7
Total outflow	162	100

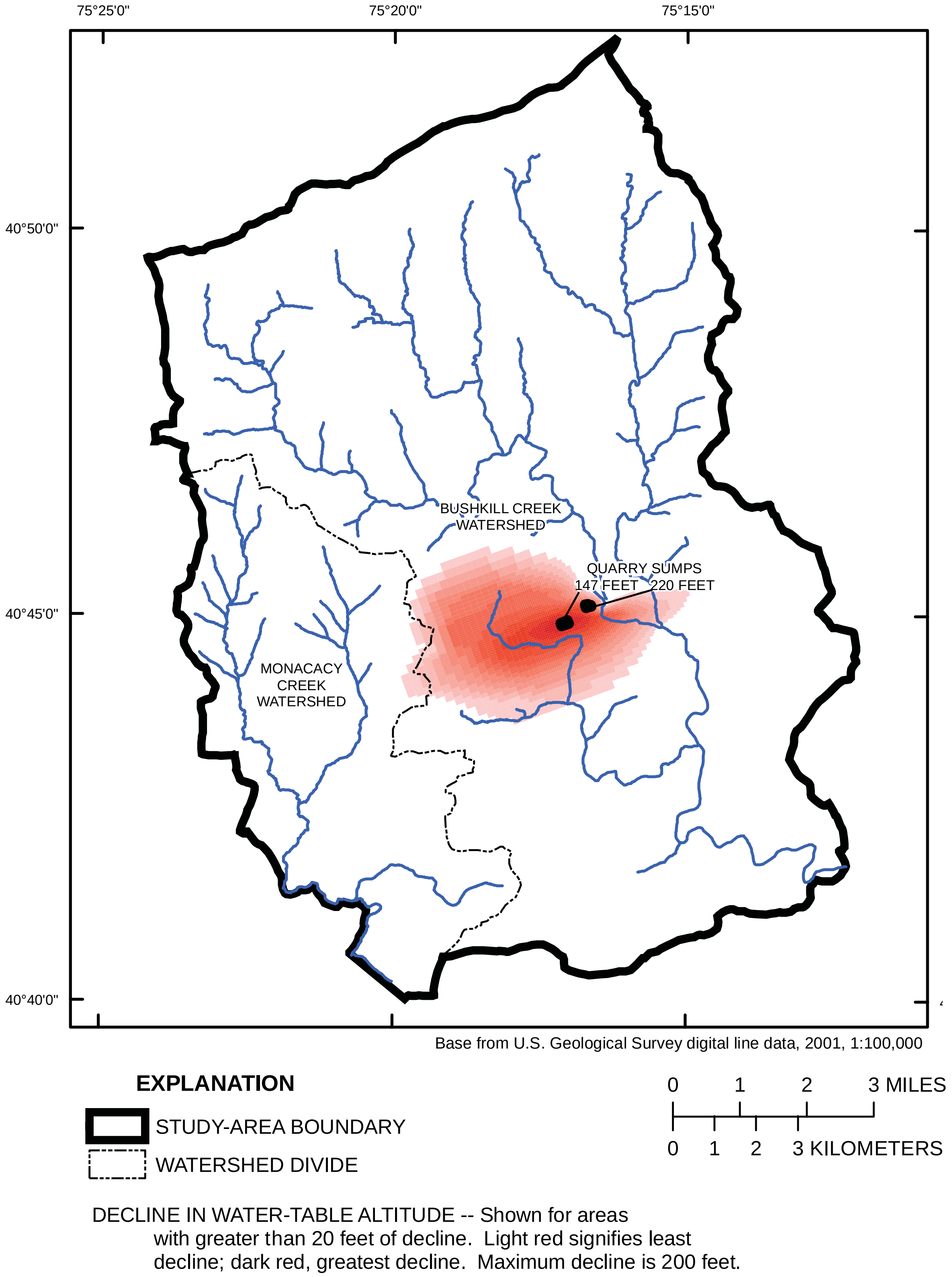
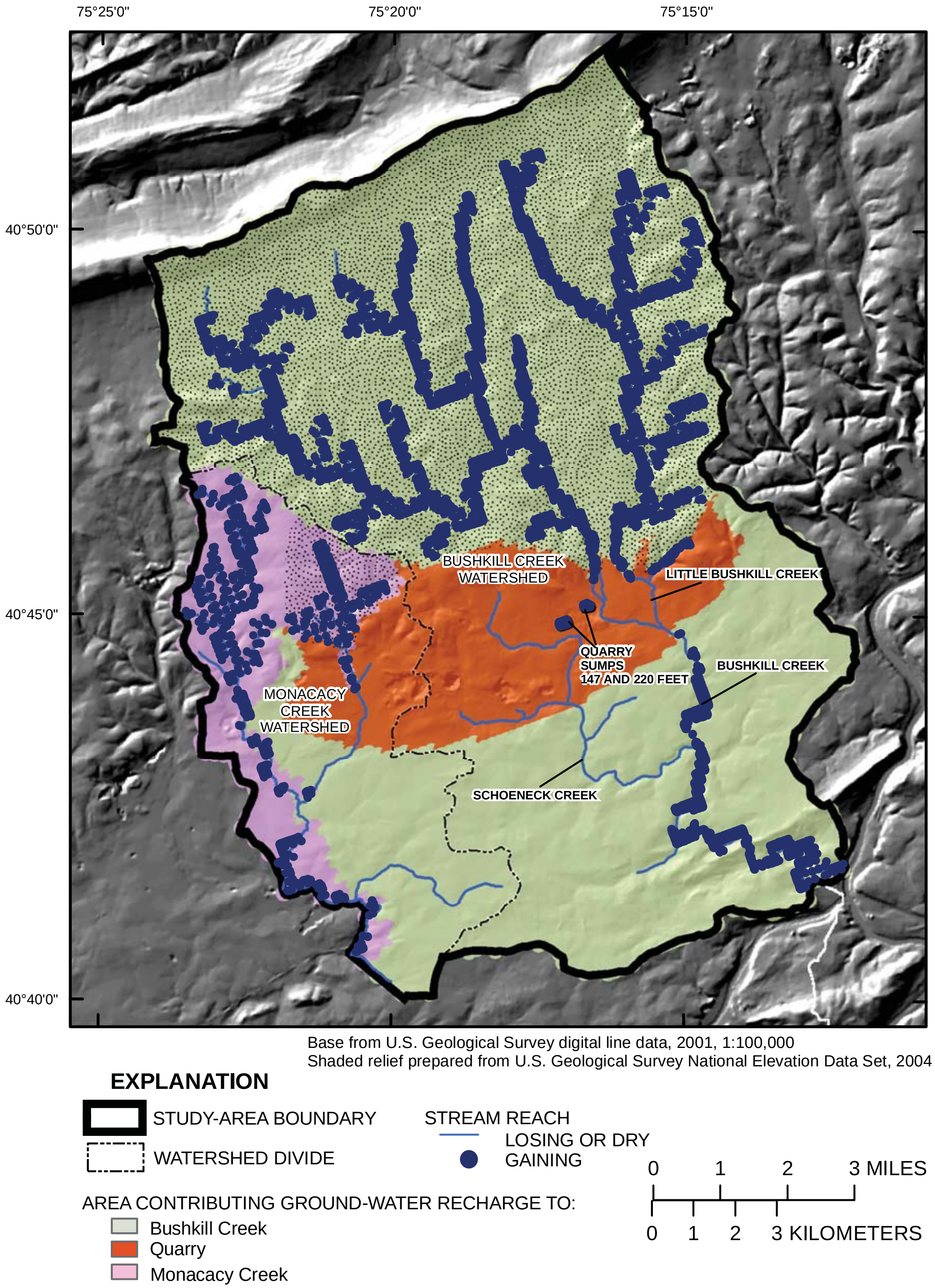


Figure 10. Simulated regional decline in water-table altitude relative to simulated predevelopment conditions in Bushkill and parts of Monocacy Creek watersheds, Northampton County, Pennsylvania, with the water table in two sumps held at altitudes of 147 and 220 feet to operate a quarry.



Base from U.S. Geological Survey digital line data, 2001, 1:100,000
Shaded relief prepared from U.S. Geological Survey National Elevation Data Set, 2004

Stippling indicates additional areas contributing recharge to streams, all or part of which is lost downstream, ultimately providing base flow to Bushkill Creek or the quarry.

Figure 11. Simulated areas contributing ground-water recharge and gaining and losing stream reaches in Bushkill and parts of Monocacy Creek watersheds, Northampton County, Pennsylvania, with the water table in two sumps held at altitudes of 147 and 220 feet to operate a quarry.

Simulations also were conducted to evaluate the effect of quarry depth on ground-water levels and flow. If the ground-water level in the deepest quarry sump were held 47 ft deeper at an altitude of 100 ft, ground-water levels were simulated to decline (fig. 12), and the ground-water discharge to the quarry increased about 4 ft^3/s. Alternately, if the ground-water level in the deepest quarry sump was held 53 ft higher at an altitude of 200 ft, ground-water levels were simulated to increase (fig. 13), and the ground-water discharge to the quarry decreased about 14 ft^3/s.

Effects of Changes in Hydraulic Conductivity

Simulations were conducted to illustrate the potential changes in ground-water/surface-water relations if the hydraulic conductivity was changed during efforts to mitigate sinkhole development. Three scenarios were tested as examples: (1) decrease in streambed hydraulic conductivity, (2) decrease in hydraulic conductivity of a highly transmissive zone, and (3) change in the ratio of horizontal anisotropy.

Streambed Hydraulic Conductivity

The basin was simulated under steady-state conditions with prescribed heads of 147 and 220 ft at two sumps to operate a quarry and with a change in the hydraulic conductivity of the streambed beneath parts of Bushkill Creek. In the reach of Bushkill Creek between streamflow sites 1-8 on figure 4, the hydraulic conductivity of the streambed was assigned a value of 0.001 ft/d to illustrate the effect of that change on water levels and inflow to the quarry. The streambed in this reach was previously assigned values from 0.01 to 30 ft/d during the model-adjustment procedure. The relative decline in ground-water levels if streambed hydraulic conductivity was decreased is shown in figure 14. The greatest changes were beneath the stream where the greatest quantity of water was being lost from the stream prior to the decrease in streambed conductivity. Lowering the streambed K caused the losses of streamflow to be nearly completely curtailed in this section and caused simulated ground-water inflow to the quarry to decrease from 74 to 45 ft^3/s.

Highly Transmissive Zone

The study area was simulated under steady-state conditions with prescribed head of 147 and 220 ft at two sumps to operate a quarry and with a decrease in the hydraulic conductivity of a highly transmissive zone that had been postulated as a probable conduit for ground-water flow (Hazlett-Kincaid, Inc., 2002, p. 4 and fig. 3). A relatively impermeable plug of material with hydraulic conductivity of 0.01 ft/d was simulated in the model as shown in figure 15. Simulations indicated that ground-water levels would rise to the east of the plug and would decline to the west of the plug (fig. 15). Ground-water levels would rise east of the plug because a larger gradient would be needed to drive ground water through the less permeable rocks that surround the simulated highly transmissive zone. Eventually, the water would flow around the plug as simulated in this example, but inflow to the quarry decreased from 74 to 53 ft^3/s.

If the relatively impermeable plug was simulated in addition to decreasing the hydraulic conductivity of the streambed between sites 1-8 (fig. 14), the resulting water-level declines are shown in figure 16. The water-level change was similar to that shown in figure 14, but the area of greatest decline shifted to the west because of the build-up of water east of the plug. Ground-water inflow to the quarry was simulated to decrease from 74 to 42 ft^3/s.

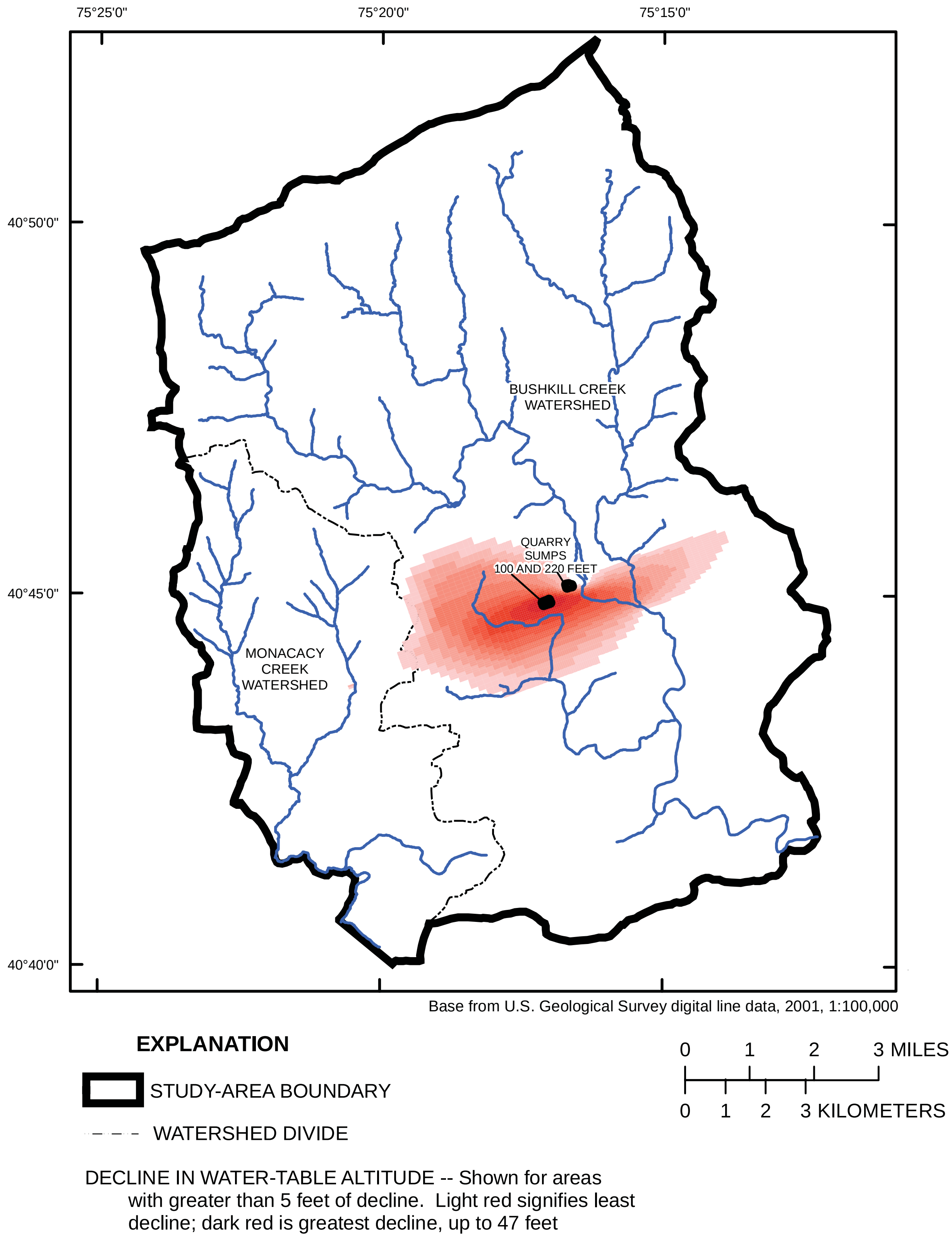
Horizontal Anisotropy Ratio

The model was constructed to incorporate the concept that the hydraulic conductivity would be greatest along the strike because of preferential flow within fractures developed parallel to bedding. Model adjustments indicated results were highly sensitive to the horizontal anisotropy value. But because this parameter was highly correlated with the hydraulic conductivity assigned to the carbonate rocks [parameter K(carb) in table 3], the horizontal anisotropy ratio could be set to 1:1 and K(carb) could be adjusted to produce a model that fits the data with about the same residuals as for the model with an anisotropy ratio of 6:1. The area contributing ground-water recharge to the quarry with isotropic hydraulic conductivity for the carbonate rocks is shown in figure 17. Comparison with figure 11 gives a qualitative measure of the sensitivity of the model to horizontal anisotropy and shows the considerable uncertainty in these preliminary model simulations.

Assumptions and Limitations of the Preliminary Model

Because the purpose of this report is to show the preliminary status of the study and to help guide ongoing data collection, the limitations of the results presented are significant and need to be recognized. Fundamentally, the study was conducted with readily available datasets and was designed to be a “first cut” for demonstrating the potential usefulness of ground-water modeling for simulating predevelopment conditions and the possible effects of sinkhole-mitigation activities. A thorough evaluation of the conceptual model, analysis of model sensitivity, and determination of effects of boundary conditions have not yet been conducted.

The ground-water flow model of Bushkill Creek and parts of Monocacy Creek watersheds was based on a simplified 2-dimensional conceptualization of steady-state ground-water flow in aquifers characterized by fractured bedrock and karst features. Although there was reasonably good agreement between measured and simulated water levels and ground-water discharge as viewed on a regional perspective, the poor agreement of measured water levels when viewed at the local scale (fig. 7B) may be an indication that the extreme heterogeneity of the carbonate rocks was not well represented by the model at that scale.



Base from U.S. Geological Survey digital line data, 2001, 1:100,000

DECLINE IN WATER-TABLE ALTITUDE -- Shown for areas with greater than 5 feet of decline. Light red signifies least decline; dark red is greatest decline, up to 47 feet

Figure 12. Simulated decline in the water-table altitude in Bushkill and parts of Monocacy Creek watersheds, Northampton County, Pennsylvania, caused by lowering the water table in the deepest quarry sump from an altitude of 147 to 100 feet.

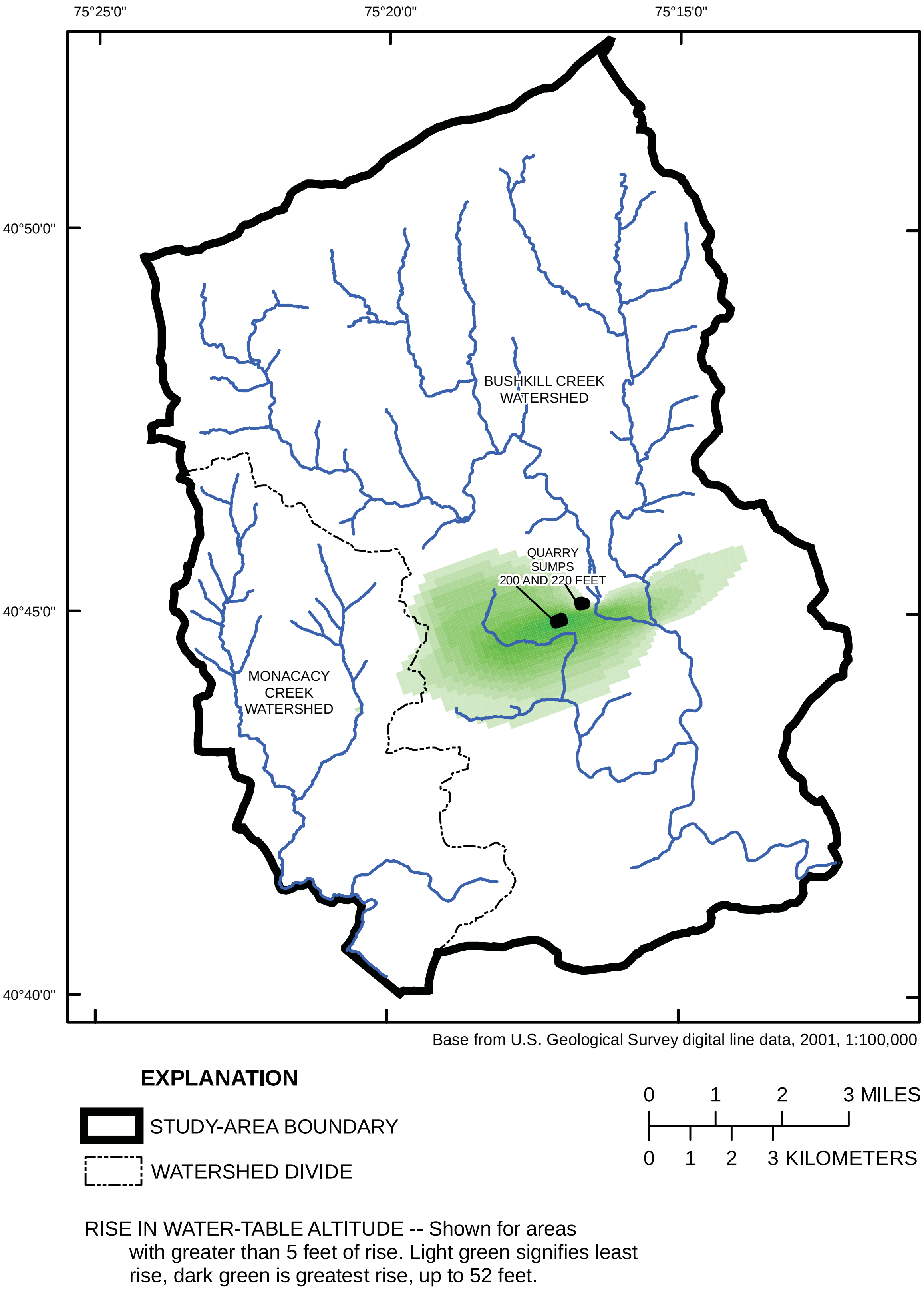
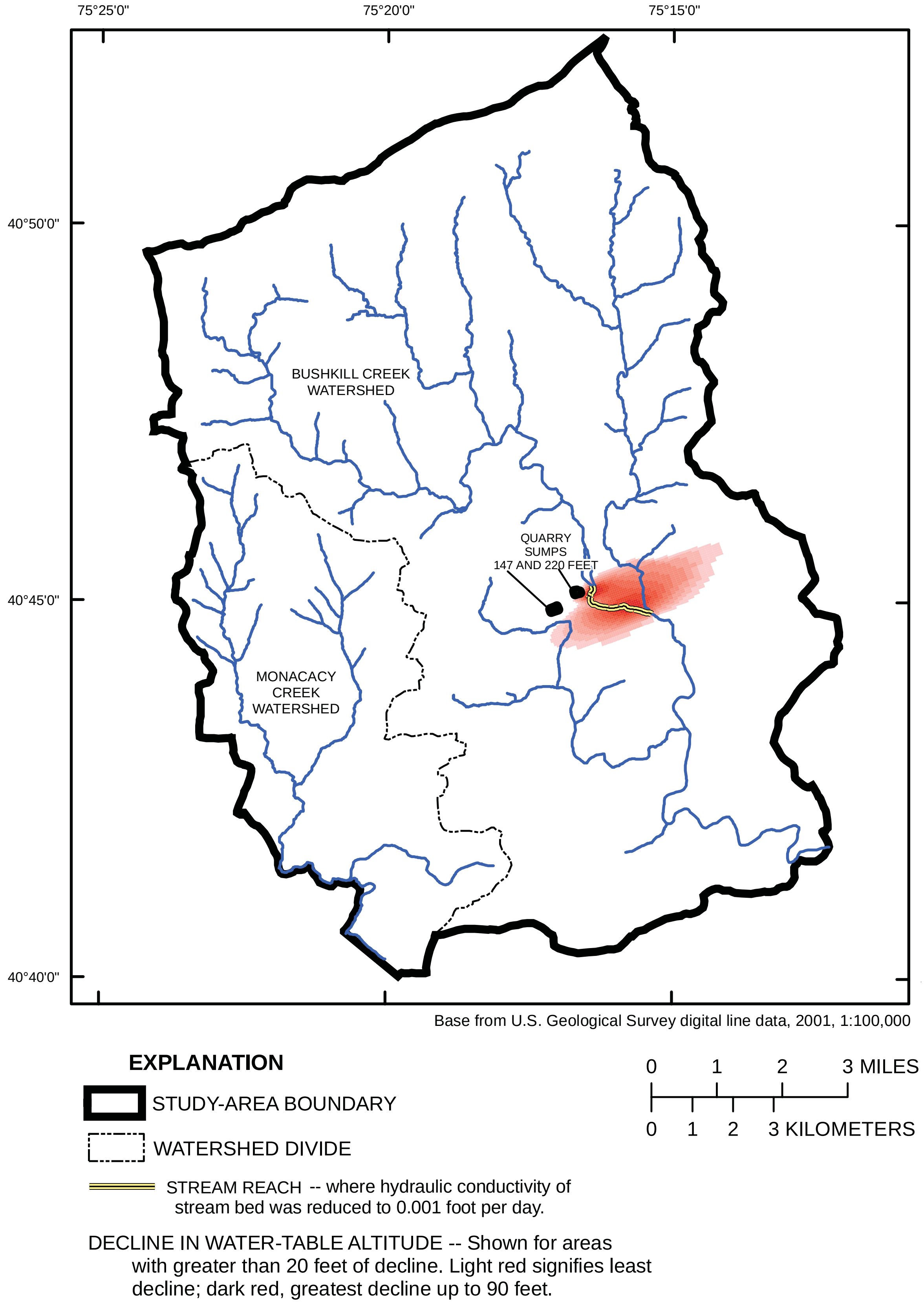


Figure 13. Simulated rise in water-table altitude in Bushkill and parts of Monocacy Creek watersheds, Northampton County, Pennsylvania, caused by raising the water table in the deepest quarry sump from an altitude of 147 to 200 feet.



Base from U.S. Geological Survey digital line data, 2001, 1:100,000

Figure 14. Simulated decline in the water-table altitude in Bushkill and parts of Monocacy Creek watersheds, Northampton County, Pennsylvania, caused by lowering the hydraulic conductivity of the streambed in the area of greatest streamflow loss.

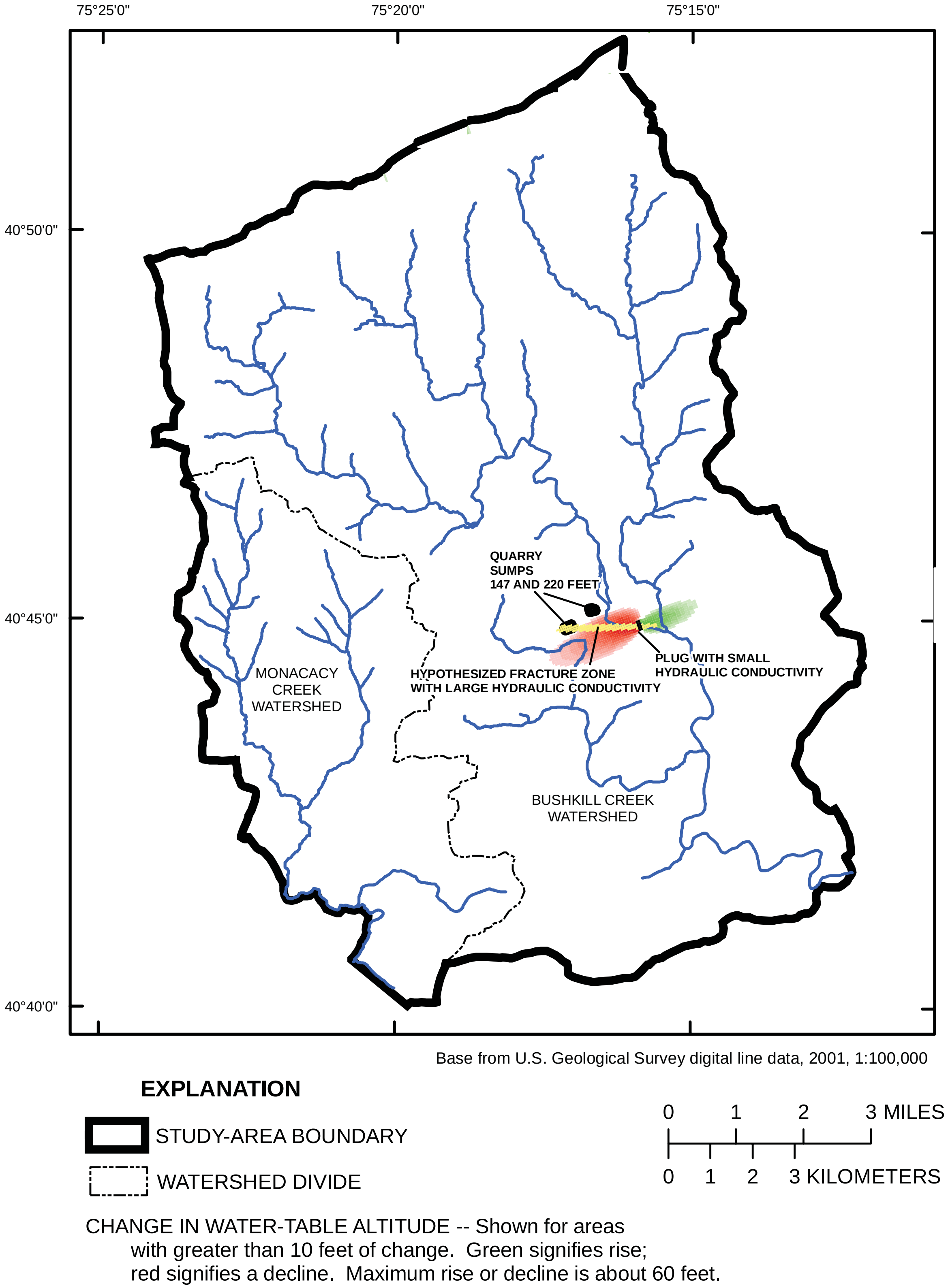
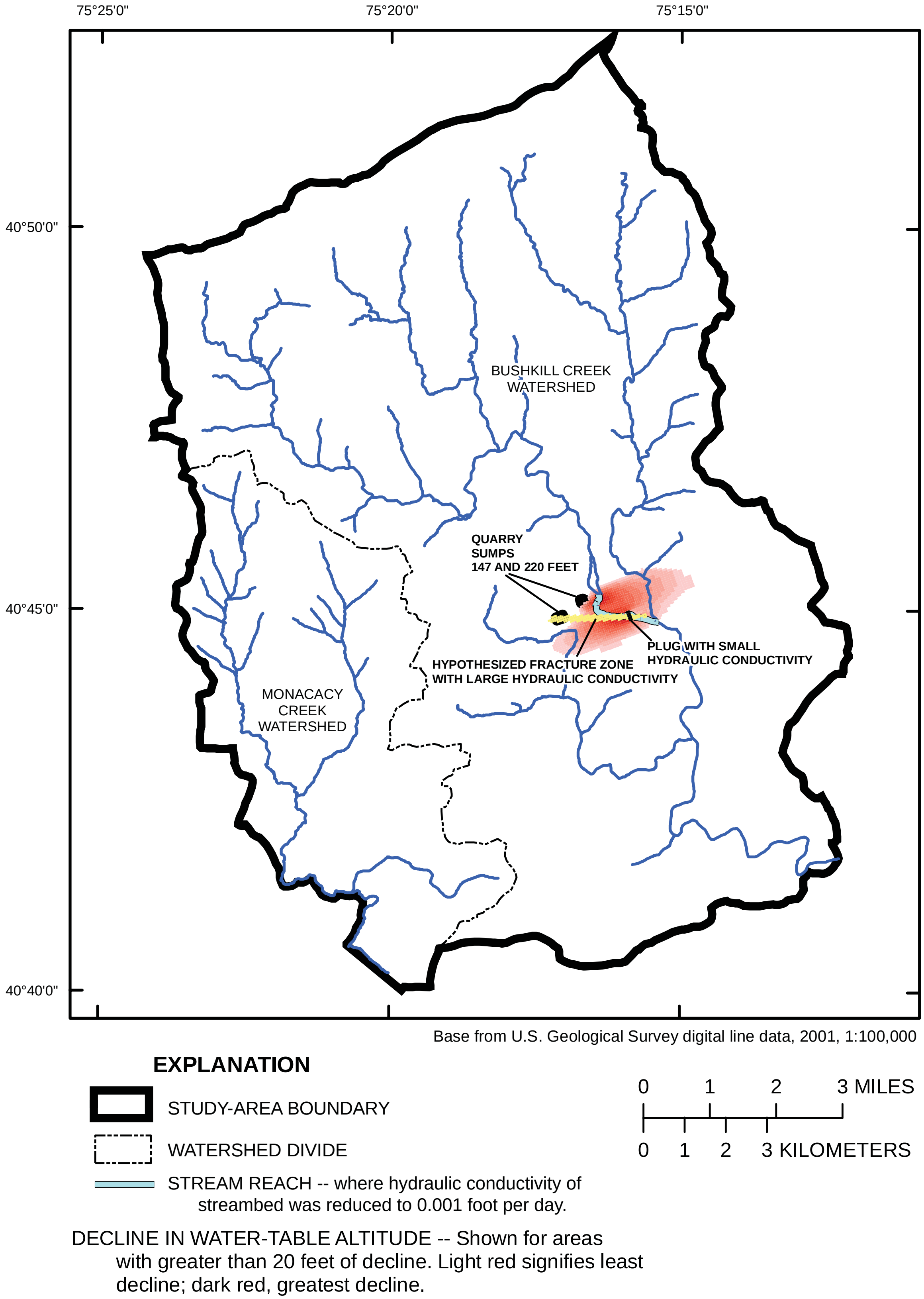
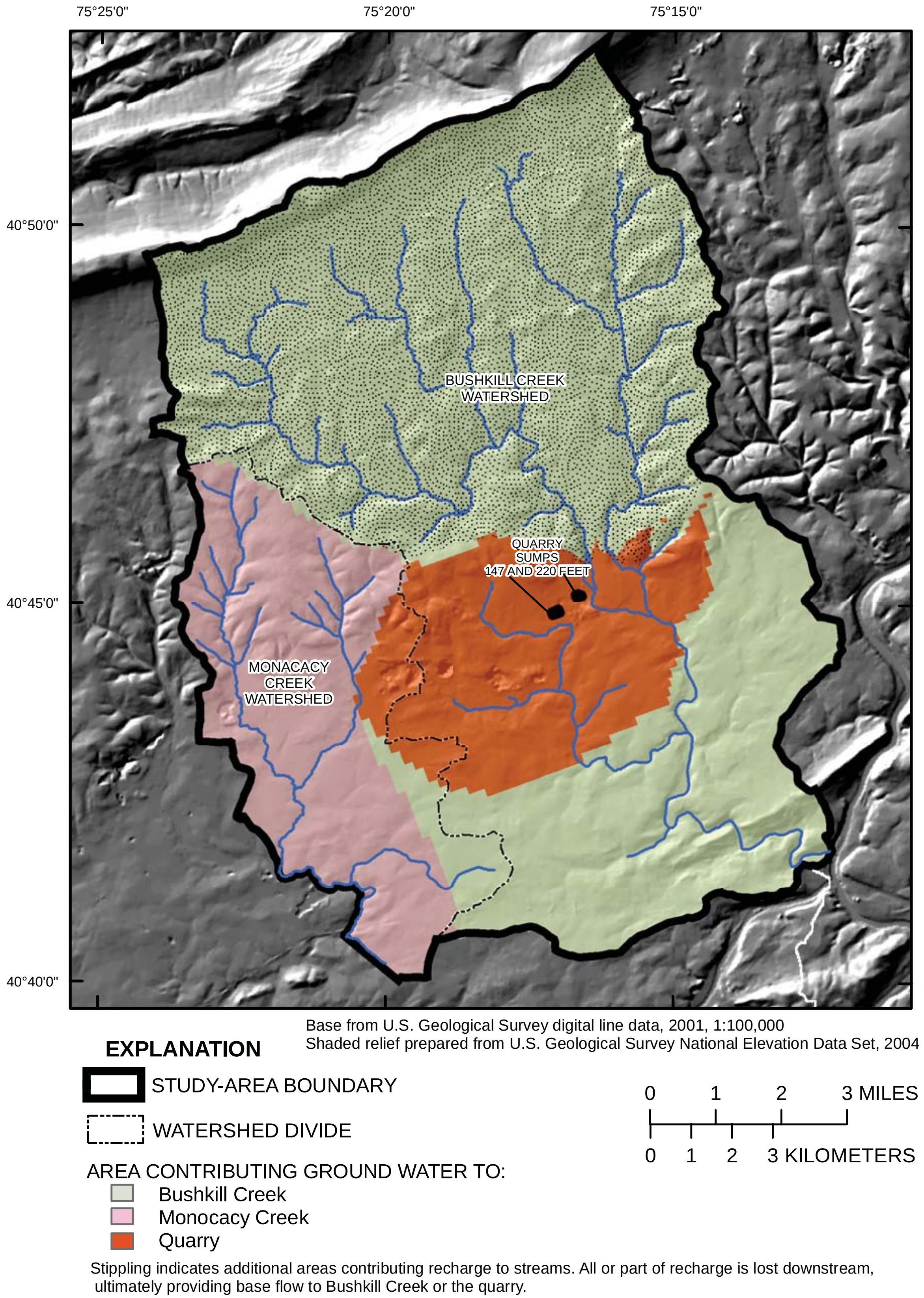


Figure 15. Simulated change in water-table altitude in Bushkill and parts of Monocacy Creek watersheds, Northampton County, Pennsylvania, caused by decreasing the hydraulic conductivity of a fracture zone with large hydraulic conductivity.



Base from U.S. Geological Survey digital line data, 2001, 1:100,000

Figure 16. Simulated decline in the water-table altitude in Bushkill and parts of Monocacy Creek watersheds, Northampton County, Pennsylvania, caused by decreasing the hydraulic conductivity of both the streambed and a fracture zone that had large hydraulic conductivity.



Base from U.S. Geological Survey digital line data, 2001, 1:100,000
Shaded relief prepared from U.S. Geological Survey National Elevation Data Set, 2004

Stippling indicates additional areas contributing recharge to streams. All or part of recharge is lost downstream, ultimately providing base flow to Bushkill Creek or the quarry.

Figure 17. Simulated areas contributing ground-water recharge to streams and a quarry assuming isotropic hydraulic conductivity for carbonate rocks, Bushkill and parts of Monocacy Creek watersheds, Northampton County, Pennsylvania.

Several important assumptions were made about ground-water recharge in the preliminary modeling that directly affected the water budgets and size of the simulated areas contributing ground-water recharge to the quarry. Recharge to the ground-water system was assumed to be spatially and temporally uniform, and the uniform rate of 15 in/yr was based on hydrograph analysis for streamflow-gaging stations outside of the study area. Ground-water recharge rates probably varied in the study area, especially between the shaley uplands and carbonate-rock lowland. In addition, the magnitude of ground-water recharge to the carbonate rocks provided from infiltration of streamflow was not well known, but one seepage study showed that it was a significant source of recharge. Simulations showed the size of the area contributing ground-water recharge to the quarry was very sensitive to the recharge rate and infiltration of streamflow.

Results of model simulations were shown to be most sensitive to recharge, horizontal anisotropy, hydraulic conductivity of the carbonate rocks, and hydraulic conductivity of a hypothesized highly transmissive zone. The effect of changing values for these hydrologic properties was not thoroughly tested in this preliminary study; however, it was found that the hydraulic conductivity of carbonate rocks could be simulated as isotropic without introducing significantly greater error in residuals (difference between measured and simulated values). Simulations showed the shape of the area contributing recharge to the quarry was very sensitive to a change in horizontal anisotropy. The anisotropy ratio also greatly affected the water budgets and the location of the ground-water divide between Bushkill and Monocacy Creek watersheds.

The data used for adjustment of the model were of variable quality, but for preliminary simulations, the strategy was to use all the readily available data. During the parameter-estimation process, all water-level data were treated as if they were of similar quality, though it was known that the quality of data differed. Proper weighting of the water-level data would help provide better results for aquifer parameters. Results are also limited in that not all known sources of ground-water withdrawals were included. Model calibration indicated some key aquifer properties were not well defined.

An inherent limitation of the model was in the assumption that the hydraulic properties of fractures and conduits were represented by an equivalent set of hydraulic properties for a porous medium. The continuum approach is usually adequate for simulating steady-state ground-water flux at large scales incorporating numerous fractures but may be invalid at the local scale if only a few discrete fractures or conduits control ground-water flow paths. In the ground-water flow model, a fracture zone or conduit having high transmissivity had been theorized and was simulated explicitly in the model; however, many other zones of preferential flow probably exist that were not explicitly included.

Suggestions for Future Data Collection

Additional measurements and analysis would help determine water budgets and evaluate the interaction between ground water and surface water. The following are suggestions for future data collection that have been identified for improving the understanding of regional ground-water flow in the Bushkill and Monocacy Creek watersheds.

- Synoptic streamflow measurements—The simulated effect of a quarry in the ground-water system was inversely related to the amount of the quarry discharge believed to originate from stream infiltration. Thus, additional synoptic measurements of streamflow in Bushkill, Little Bushkill, Monocacy, and Schoeneck Creek watersheds are needed to quantify infiltration of streamflow. Measurements near the average annual base-flow conditions would provide better flow targets for adjusting parameters in the steady-state model than measurements conducted during low-flow conditions. In addition, more measurements would be needed to better quantify the large streamflow losses in Bushkill Creek between streamflow measurement sites 5 and 7 (fig. 4) to quantify the relation between discharge rate and loss.

- Continuous monitoring—Long-term continuous monitoring of streamflow in Bushkill, East Branch Monocacy, and Schoeneck Creeks would provide a record of total runoff, documenting the response of the watershed to climate and land-use changes. Continuous monitoring captures events, such as storms, that are impossible to record with synoptic measurements. Streamflow-gaging stations installed as upstream/downstream pairs would allow a determination of gains and losses between stations.

- Water-use data—Incorporation of historical water withdrawals and discharges would provide a more complete accounting of all terms in the basin water budget. Other data on quarry operation, ground-water pumping for public and industrial supply, and streamflow could be incorporated.

- Water-level data—Synoptic measurements of ground-water levels in wells would improve knowledge of the water-table configuration and provide better ground-water-level data for model adjustments than the miscellaneous water-level data available from the GWSI database. Ideally, the altitudes of wells should be surveyed so that an accurate datum is available for each well. Continuous monitoring of water levels in wells near streams and quarries would provide a record of the transient response to natural and anthropogenic events.

- Streambed surveys—Surveys of the hydraulic gradient beneath stream channels would help establish the extent of gaining and losing reaches under differing hydrologic conditions and season. These surveys can be conducted with a potentiomanometer as described in Winter and others (1988).

- Tracer studies—Tracer studies are the best method for determining the direction and velocity of ground-water flow. Tracer studies could be conducted on losing reaches of Bushkill, Little Bushkill, Monocacy, and Schoeneck Creeks or at individual sinkholes.

Summary

This report, prepared in cooperation with the Pennsylvania Department of Environmental Protection, Office of Mineral Resources Management, provides a preliminary analysis of water budgets and generalized ground-water/surface-water interactions for Bushkill and parts of Monocacy Creek watersheds in Northampton County, Pa., by use of a ground-water flow model. Preliminary simulations of ground-water flow are presented to show the status of work using data available through September 2005, and to help guide ongoing data collection in Bushkill Creek watershed. This study could begin a process for obtaining hydrologic data needed for a comprehensive regional evaluation of the ground-water resources in the carbonate rocks of the Great Valley in eastern Pennsylvania. Such a regional evaluation could provide scientific information to managers for planning sustainable development, water use, and resource extraction while minimizing losses from natural hazards.

The study area is 101 mi^2 and includes Bushkill Creek watershed and the eastern part of Monocacy Creek watershed in Northampton County, within the Great Valley Section of the Ridge and Valley Physiographic Province in Pennsylvania. Part of Monocacy Creek watershed was included in the study area so that the ground-water divide between the Bushkill and Monocacy basins would not be predetermined in the model simulations.

The finite-difference computer code MODFLOW-2000 was used with the particle-tracking program MODPATH to simulate 2-dimensional ground-water flow and to display results. Simulated values of recharge, hydraulic conductivity, horizontal anisotropy, and streambed hydraulic conductivity were adjusted by trying to match measurements of (1) water levels in 60 wells available from the USGS Ground-Water Site Inventory (GWSI) database, (2) water levels in 18 observation wells provided by PaDEP, (3) ground-water inflow to the quarry, and (4) gains and losses of stream base flow in a reach of Bushkill Creek. Simulations of the water budget and ground-water/surface-water interactions of the Bushkill Creek watershed were conducted by the adjusted model with the following hydrologic properties—uniform recharge of 15 in/yr, hydraulic conductivity of the Martinsburg Formation ranging from 0.14 to 1.8 ft/d, hydraulic conductivity of carbonate-rock aquifers ranging from 8.8 to 61 ft/d along model rows (along strike of geologic units), hydraulic conductivity for a hypothesized zone of large transmissivity of 1,013 ft/d, and anisotropy of 6:1 for the carbonate rocks (ratio of hydraulic conductivity along the strike of geologic units to hydraulic conductivity along the dip direction). Hydraulic conductivity of the streambed of Bushkill Creek ranged from 0.01 to 500 ft/d. The small value of hydraulic conductivity was used where the stream channel was known to have been lined; the large values of hydraulic conductivity were used where sinkholes were known to exist in the streambed, and in some other areas where the stream flows over carbonate bedrock.

Preliminary simulations of average, steady-state ground-water flow in Bushkill Creek watershed were conducted for (1) predevelopment conditions, (2) a water table lowered for quarry operations, and (3) changes in hydraulic conductivity of the streambed and aquifer. Simulations of predevelopment conditions indicated the divide between the Bushkill and Monocacy Creek ground-water basins may not coincide with the topographic divide and as much as 14 percent of the ground-water discharge to Bushkill Creek could originate from the Monocacy Creek watershed. Under predevelopment conditions, ground-water discharged to Bushkill Creek throughout all reaches, but all of Schoeneck Creek and parts of Monocacy Creek did not receive ground-water discharge.

Simulations with the water table lowered to an altitude of 147 ft for quarry operations indicated the quarry captured ground-water recharge and streamflow throughout about a 14-mi^2 area, causing the proportion of inflow diverted from Monocacy Creek watershed to increase and reaches of Bushkill and Little Bushkill Creeks to change from gaining to losing streams. In these simulations, ground-water discharge to the quarry accounted for 46 percent of ground-water discharge from the Bushkill Creek watershed. Changes in the depth that the water table was held near a quarry affected the simulated water table and water budget. Lowering the deepest quarry sump to an altitude of 100 ft caused simulated ground-water discharge to the quarry to increase about 4 ft^3/s, and raising the deepest sump to an altitude of 200 ft caused the simulated discharge to the quarry to decrease about 14 ft^3/s.

Simulations of changes in the hydraulic conductivity of the streambed and the aquifer indicated that ground-water/surface-water interactions were sensitive to changes in those parameters. Decreasing the hydraulic conductivity of the streambed of Bushkill Creek to 0.001 ft/d in the reach of large losses caused ground-water levels to decline and simulated ground-water discharge to the quarry to decrease from 74 to 45 ft^3/s. Decreasing the hydraulic conductivity of the hypothesized highly transmissive zone with a plug of relatively impermeable material caused ground-water levels to increase east of the plug and decline west of the plug and simulated discharge to the quarry to decrease to 53 ft^3/s. If the relatively impermeable plug was simulated in addition to decreasing the hydraulic conductivity of the streambed, ground-water levels declined, but the area of greatest decline shifted to the west compared to the simulation without the plug, and ground-water inflow to the quarry decreased to 42 ft^3/s.

Preliminary results of the study have significant limitations, which need to be recognized by the user. The results demonstrated the usefulness of ground-water modeling with available datasets, but as more data become available through field studies, a more complete evaluation could be conducted of the preliminary assumptions in the conceptual model, model sensitivity, and effects of boundary conditions. At the local scale, especially, the poor agreement between simulated and measured water levels may be an indication that the heterogeneity of the carbonate rocks was not being well represented in the model, suggesting that the model should be used with caution for making predictions at the local scale.

Additional streamflow and ground-water-level measurements would be needed to better quantify recharge and aquifer properties, particularly the anisotropy of carbonate rocks. Measurements of streamflow losses at average, steady-state hydrologic conditions would provide a more accurate estimate of ground-water recharge from this source, which directly affects water budgets and contributing areas simulated by the model. Measurements of water levels in wells would be needed to better characterize the water-table configuration.

References Cited

Berg, T.M., Edmunds, W.E., Geyer, A.R., Glover, A.D., Hoskins, D.M., MacLachlan, D.B., Root, S.I., Sevon, W.D., and Socolow, A.A., comps., 1980, Geologic map of Pennsylvania: Pennsylvania Geological Survey, 4th ser., Map 1, scale 1:250,000, 3 sheets.

Earth Tech, Inc., 2002, Final comprehensive groundwater study, groundwater monitoring plan and Bushkill Creek and sinkhole remediation plan, PADEP Non coal surface mine permit application no. 747sm2ac5, 136 p.

Hall, G.M., 1934, Ground water in southeastern Pennsylvania: Pennsylvania Geological Survey, 4th ser., Water Resources Report 2, 255 p., 1 plate.

Hazlett-Kincaid, Inc., 2002, Simulation of current and future water table conditions at the Hercules Cement Quarry, Stockertown Pennsylvania, in Earth Tech, Inc., 2002, Final comprehensive groundwater study, groundwater monitoring plan and Bushkill Creek and sinkhole remediation plan, PADEP Non coal surface mine permit application no. 747sm2ac5, 136 p.

Harbaugh, A.W., Banta, E.R., Hill, M.C., and McDonald, M.G., 2000, MODFLOW-2000, the U.S. Geological Survey modular ground-water flow model—User guide to modularization concepts and the ground-water flow process: U.S. Geological Survey Open-File Report 00-92, 121 p.

Hill, M.C., Banta, E.R., Harbaugh, A.W., 2000, MODFLOW-2000, the U.S. Geological Survey modular ground-water flow model—User guide to the observation, sensitivity, and parameter-estimation processes and three post-processing programs: U.S. Geological Survey Open-File Report 00-184, 209 p.

Kochanov, W.E., and Reese, S.O., 2003, Density of mapped karst features in south-central and southeastern Pennsylvania: Pennsylvania Geological Survey, 4th ser., Map 68, scale 1:300,000.

Kruseman, G.P., and de Ridder, N.A., 1990, Analysis and evaluation of pumping test data: Wageningen, the Netherlands, International Institute for Land Reclamation and Improvement, Publication 47, 377 p.

Miller, B.L., Fraser, D.M., and Miller, R.L., 1939, Northampton County, Pennsylvania: Topographic and Geological Survey, County Report 48, 496 p., 29 pls. (Reprinted 1973)

Pollock, D. W., 1994, User's guide for MODPATH/MODPATH-PLOT, VERSION 3—A particle tracking post-processing package for MODFLOW, the U.S. Geological Survey finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 94-464, 249 p.

Poth, C.W., 1972, Hydrology of the Martinsburg Formation in Lehigh and Northampton Counties, Pennsylvania: Pennsylvania Geological Survey, 4th ser., Water Resources Report 30, 52 p., 1 plate.

Prudic, D.E., 1989, Documentation of a computer program to simulate stream-aquifer relations using a modular, finite-difference, ground-water flow model: U.S. Geological Survey Open-File Report 88-729, 113 p.

Risser, D.W., Conger, R.W., Ulrich, J.E., and Asmussen, M.P., 2005, Estimates of ground-water recharge based on streamflow-hydrograph methods—Pennsylvania: U.S. Geological Survey Open-File Report 2005-1333, 30 p.

Sevon, W.D., 2000, Physiographic provinces of Pennsylvania (4th ed.): Pennsylvnaia Geological Survey, 4th ser., Map 13, scale 1:2,000,000.

U.S. Geological Survey, 2001, Digital line graphs: U.S. Geological Survey data available on the web, accessed July 2005, at *http://edc.usgs.gov/deodata*.

U.S. Geological Survey, 2004, National elevation dataset: U.S. Geological Survey data available on the Web, accessed July 2005, at *http://ned.usgs.gov/*.

Winston, R.B., 2000, Graphical User Interface for MODFLOW, Version 4: U.S. Geological Survey Open-File Report 00-315, 27 p.

Winter, T.C., LaBaugh, J.W., and Rosenberry, D.O., 1988, The design and use of a hydraulic potentiomanometer for direct measurement of differences in hydraulic head between groundwater and surface water: Limnology and Oceanography, v. 33, no. 5, p. 1209-1214.

Wood, C.R., Flippo, H.N., Lescinsky, J.B., and Barker, J.L., 1972, Water resources of Lehigh County, Pennsylvania: Pennsylvania Geological Survey, 4th ser., Water Resources Report 31, 263 p.