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Scientific Investigations Report 2008-5041

U.S. Department of the Interior
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U.S. Geological Survey
Mark D. Myers, Director

U.S. Geological Survey, Reston, Virginia: 2008
Revised: March 24, 2011

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Suggested citation:
Risser, D.W., 2008, Spatial distribution of ground-water recharge estimated with a water-budget method for the Jordan Creek watershed, Lehigh County, Pennsylvania: U.S. Geological Survey Scientific Investigations Report 2008-5041, 26 p.

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Conversion Factors

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
mile per hour (mi/h)	1.609	kilometer per hour (km/h)
	Density	
pound per cubic foot (lb/ft^3)	0.01602	gram per cubic centimeter (g/cm^3)
	Pressure	
bar	100	kilopascal (kPa)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)

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

$$°C = (°F-32)/1.8$$

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

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

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

Spatial Distribution of Ground-Water Recharge Estimated with a Water-Budget Method for the Jordan Creek Watershed, Lehigh County, Pennsylvania

by Dennis W. Risser

Abstract

This report presents the results of a study by the U.S. Geological Survey, in cooperation with the Pennsylvania Department of Conservation and Natural Resources, Bureau of Topographic and Geologic Survey, to illustrate a water-budget method for mapping the spatial distribution of ground-water recharge for a 76-square-mile part of the Jordan Creek watershed, northwest of Allentown, in Lehigh County, Pennsylvania. Recharge was estimated by using the Hydrological Evaluation of Landfill Performance (HELP) water-budget model for 577 landscape units in Jordan Creek watershed, delineated on the basis of their soils, land use/land cover, and mean annual precipitation during 1951-2000. The water-budget model routes precipitation falling on each landscape unit to components of evapotranspiration, surface runoff, storage, and vertical percolation (recharge) for a five-layer soil column on a daily basis. The spatial distribution of mean annual recharge during 1951-2000 for each landscape unit was mapped by the use of a geographic information system.

Recharge simulated by the water-budget model in Jordan Creek watershed during 1951-2000 averaged 12.3 inches per year and ranged by landscape unit from 0.11 to 17.05 inches per year. Mean annual recharge during 1951-2000 simulated by the water-budget model was most sensitive to changes to input values for precipitation and runoff-curve number.

Mean annual recharge values for the crop, forest, pasture, and low-density urban land-use/land-cover classes were similar (11.2 to 12.2 inches per year) but were substantially less for high-density urban (6.8 inches per year), herbaceous wetlands (2.5 inches per year), and forested wetlands (1.3 inches per year). Recharge rates simulated for the crop, forest, pasture, and low-density urban land-cover classes were similar because those land-use/land-cover classes are represented in the model with parameter values that either did not significantly affect simulated recharge or tended to have offsetting effects on recharge. For example, for landscapes with forest land cover, values of runoff-curve number assigned to the model were smaller than for other land-use/land-cover classes (causing more recharge and less runoff), but the maximum depth of evapotranspiration was larger than for other land-use/land-cover classes because of deeper root penetration in forests (causing more evapotranspiration and less recharge). The smaller simulated recharge for high-density urban and wetland land-use/land-cover classes was caused by the large values of runoff-curve number (greater than 90) assigned to those classes. The large runoff-curve number, however, certainly is not realistic for all wetlands; some wetlands act as areas of ground-water discharge and some as areas of recharge.

Simulated mean annual recharge computed by the water-budget model for the 53-square-mile part of the watershed upstream from the streamflow-gaging station near Schnecksville was compared to estimates of recharge and base flow determined by analysis of streamflow records from 1967 to 2000. The mean annual recharge of 12.4 inches per year simulated by the water-budget method for 1967-2000 was less than estimates of mean annual recharge of 19.3 inches per year computed from the RORA computer program and base flow computed by the PART computer program (15.1 inches per year).

In theory, the water-budget method provides a practical tool for estimating differences in recharge at local scales of interest, and the watershed-average recharge rate of 12.4 inches per year computed by the method is reasonable. However, the mean annual surface runoff of 4.5 inches per year simulated by the model is unrealistically small. The sum of surface runoff and recharge simulated by the water-budget model (16.9 inches per year) is 7 inches per year less than the streamflow measured at the gaging station near Schnecksville (23.9 inches per year) during 1967-2000, indicating that evapotranspiration is overestimated by the water-budget model by that amount. This discrepancy casts some doubt about the accuracy of the results from the water-budget model–including recharge rates. Although incorrect estimates of input parameters could be responsible for the apparent overestimate of evapotranspiration, limitations in the model algorithms also could be responsible.

Introduction

Ground-water recharge can be defined as any water that moves from land surface to the water table (Heath, 1983, p. 4). Recharge is a major component of the water budget of any watershed in Pennsylvania, but because it is almost impossible to measure directly, the magnitude and variability of recharge rates are not well known. In recent years, there has been interest in obtaining more detailed knowledge about the spatial variability of ground-water recharge rates. This interest stems partly from recent droughts and from legislation requiring an update of the State Water Plan for Pennsylvania, calling for an assessment of “prime recharge areas” and “recharge capacity” as part of an inventory of ground-water resources (Commonwealth of Pennsylvania, 2002). Additionally, there is a growing realization that land-use changes can affect ground-water recharge rates and that ground-water resources in rapidly developing areas may not be sustainable in drought years.

Many approaches for estimating ground-water recharge are available, but for watershed-scale estimates in humid regions, the most practical approaches involve either estimating recharge from streamflow records or from the residual term of a water budget. Analysis of streamflow records provides an estimate of ground-water recharge averaged over the watershed area upstream from a streamflow-gaging station. Such estimates usually are derived by separating the base-flow component of the stream hydrograph and making the assumption that base flow, the part of streamflow usually attributed to ground-water discharge, is equal to recharge. Because separation of the streamflow hydrograph is subjective and can be determined by different methods (for example—Pettyjohn and Henning, 1979; Rutledge, 1998; Arnold and others, 1995; Wahl and Wahl, 1988), considerable uncertainty exists about which base-flow estimate is the most appropriate representative of recharge. Recharge can also be estimated from streamflow records by use of the computer program RORA (Rutledge, 1998). The RORA program uses a recession-curve displacement technique to estimate ground-water recharge from each storm period, based on a one-dimensional analytical model of ground-water discharge to a fully penetrating stream in an idealized aquifer with uniform spatial recharge (Rorabaugh, 1964; Glover, 1964). This approach, although less subjective than base-flow separation, assumes that the hydrology of real watersheds can be reasonably approximated by a simple, idealized analytical model.

Commonly, however, estimates of recharge are needed for ungaged watersheds or for areas smaller than the area upstream from a streamflow-gaging station. In such cases, a water budget computed for individual landscapes within a watershed, which has different types of vegetation, relief, or soils, has the potential to discriminate differences in recharge rates among those landscapes. The water-budget approach estimates recharge as the residual term in a water-budget equation in which the other hydrologic inflows, outflows, and changes in storage are measured or indirectly determined. In this study, the water-budget model uses daily precipitation as inflow to a landscape unit; it computes daily evapotranspiration, surface runoff, vertical percolation (recharge), and changes in storage among five soil layers. The ability to map the spatial variability of recharge for differing landscapes within a watershed was investigated in this study conducted in cooperation with the Pennsylvania Department of Conservation and Natural Resources, Bureau of Topographic and Geologic Survey. Results should have applicability for land-use planning and water-management projects.

Purpose and Scope

This report describes a method for mapping the spatial distribution of ground-water recharge at the sub-watershed scale in Pennsylvania. The method involved computing recharge by using a water-budget model and mapping the distribution of mean annual recharge by use of a geographic information system (GIS), as described by Jyrkama and others (2002) for a study in the Coastal Plain of New Jersey. Because the Coastal Plain physiography is not representative of much of Pennsylvania, the methodology was tested in the Jordan Creek watershed in Lehigh County, a setting with diverse topography and bedrock geology representative of rapidly developing areas in southeastern Pennsylvania (fig. 1). This report presents a map showing spatial variability of recharge for the Jordan Creek watershed and describes the water-budget model, the model input data required to represent the watershed, and factors affecting the results. Recharge estimates from the water-budget method were compared to other estimates from streamflow-hydrograph methods. Results from the Jordan Creek watershed illustrate the applicability of the method to other watersheds.

Previous Investigations

As outlined in recent summary papers, numerous approaches, varying in complexity and data requirements, have been used to estimate recharge (Nimmo and others, 2005; Scanlon and others, 2002). In the Jordan Creek watershed, several methods for estimating recharge (along with other water-budget terms) have been used.

Wood and others (1972, p. 25) computed a long-term water budget for Jordan Creek watershed for 1946-62 but did not include an estimate of ground-water recharge. The water budget showed that streamflow and underflow together averaged 23.9 in/yr. Because ground-water recharge provides a portion of the streamflow (surface runoff provides the remainder), it is reasonable to deduce that mean annual recharge for the period was some amount less than the sum of streamflow and underflow.

Waltman and others (1997, fig. 4) computed monthly soil-water budgets for Pennsylvania landscapes for the period 1961-90. The mean annual soil-moisture surplus (precipitation minus potential evapotranspiration) was mapped for the State. For Jordan Creek watershed, the soil-moisture surplus from the statewide map was about 16 in/yr. Because actual evapotranspiration usually is less than the potential evapotranspiration, the soil-moisture surplus can be viewed as the minimum quantity of water available for ground-water recharge and surface runoff.

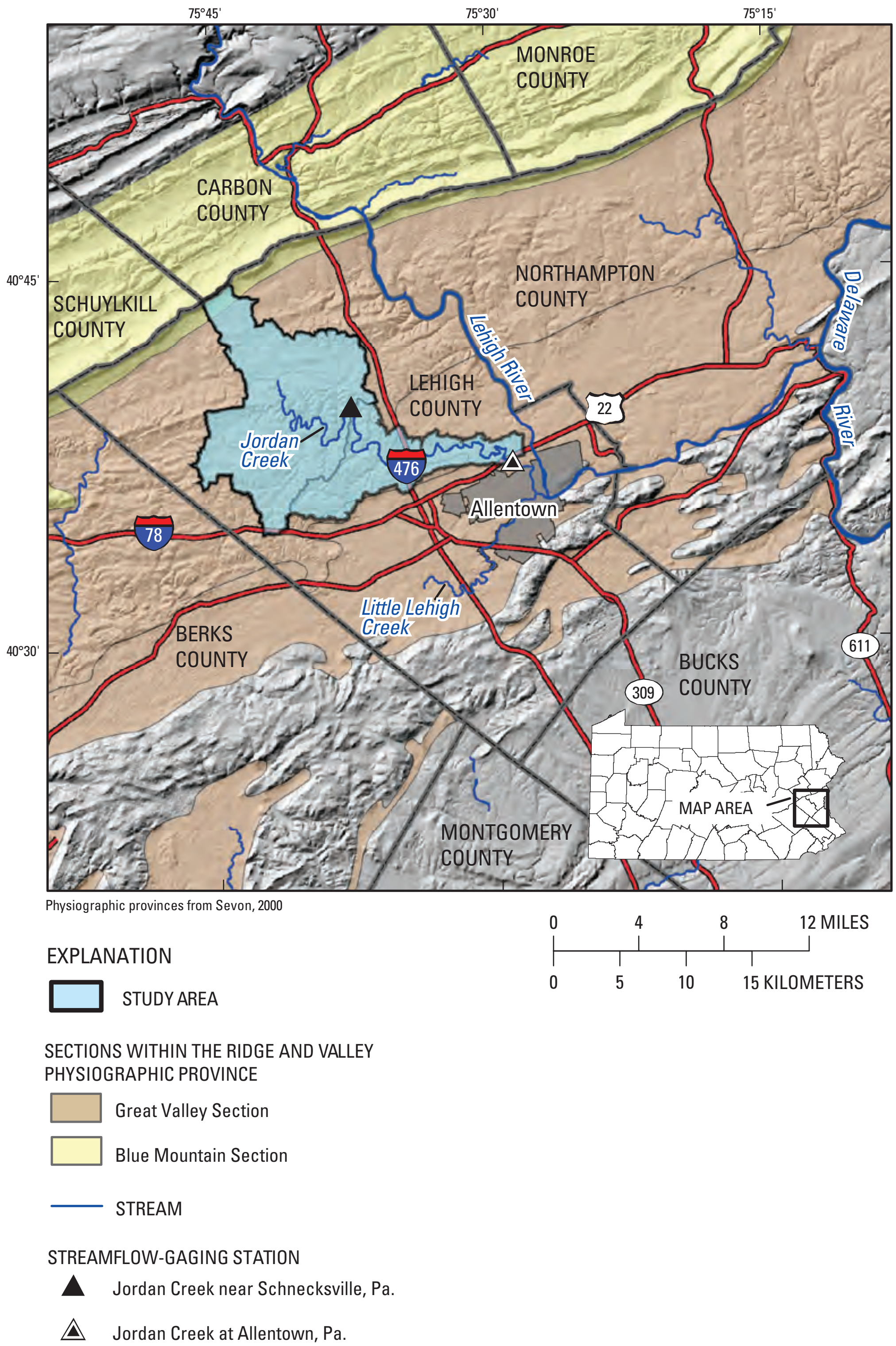


Figure 1. Location of the study area in Jordan Creek watershed, Lehigh County, Pa.

In Pennsylvania, recharge estimates have recently been made by analysis of streamflow records from gaging stations using both the recession-curve-displacement and base-flow separation approaches (Risser and others, 2005a). Estimates were made for two gaging stations in Jordan Creek watershed—Jordan Creek at Schnecksville and Jordan Creek near Allentown. Streamflow-hydrograph records were used to estimate recharge by the computer program RORA and base flow by the computer program PART (Rutledge, 1993, 1998).

On the basis of streamflow records from the gaging station at Schnecksville during 1967-2001, Risser and others (2005a) estimated mean annual recharge from the RORA method as 19.1 in. and base flow from the PART method as 15.1 in. On the basis of streamflow records during 1945-2001 from the gaging station near Allentown, estimated mean annual recharge from the RORA method was 16.6 in. and base flow from the PART method was 13.2 in. Recharge estimated from streamflow records near Schnecksville was greater than that estimated from records at the gaging station at Allentown; the same was true for estimates of base flow. Estimates at Allentown were less than for Schnecksville because of underflow of ground water in the karst aquifer beneath the Allentown gaging station. Underflow beneath the streamflow-gaging station at Allentown has been estimated to be about 4.8 in/yr (Wood and others, 1972, p. 26).

Study Area

The study area is the 76-mi^2 part of the Jordan Creek watershed upstream from the streamflow-gaging station at Allentown (fig. 1). Jordan Creek watershed is in Lehigh County, Pa., and is situated within the Great Valley and Blue Mountain Sections of the Ridge and Valley Physiographic Province (Sevon, 2000). Jordan Creek is a tributary to Little Lehigh Creek, which joins the Lehigh River at Allentown. The Lehigh River flows into the Delaware River about 15 mi east of the study area.

Streamflow of Jordan Creek has been monitored by U.S. Geological Survey (USGS) gaging stations near Schnecksville (station 01451800) since 1966 and at Allentown (station 01451850) since 1944. Jordan Creek has little or no regulation upstream from the gaging stations, so they provide streamflow data against which the water-budget method can be compared. In this report, the study area upstream from the gaging station at Allentown is referred to as the "Jordan Creek watershed," disregarding a small (6.4 mi^2) part of the watershed downstream from the gaging station.

Jordan Creek watershed has varied vegetation, land use, and bedrock geology characteristic of much of southeastern Pennsylvania. The topography of the study area is a dissected upland of moderate to steep relief in the 90 percent of the watershed underlain by shale, graywacke, sandstone, and slate of the Shawangunk and Martinsburg Formations and Hamburg sequence rocks[1] (fig. 2). The broad valley of low relief in the eastern part of the watershed is underlain by limestone and dolomite of the Jacksonburg Formation, Beekmantown Group, and Allentown Formation (Miles and others, 2001). Altitudes in the watershed range from about 1,500 ft at the northern watershed boundary to about 260 ft at the streamflow-gaging station at Allentown.

Water-Budget Method

The spatial distribution of mean annual recharge was computed using a water-budget computer model and a GIS following a methodology described by Jyrkama and others (2002). The approach for this method is to identify similar areas within the watershed (termed landscape units for this study), compute recharge for each landscape unit using the water-budget computer program, and use the GIS to assign the appropriate recharge rates for landscape units and display the data on a map. Landscape units in the Jordan Creek watershed were defined as those having the same soil type, land use/land cover, and mean annual precipitation as determined by intersecting GIS datasets for those attributes.

The water-budget method used in this study estimates recharge from the residual term in the general daily water balance:

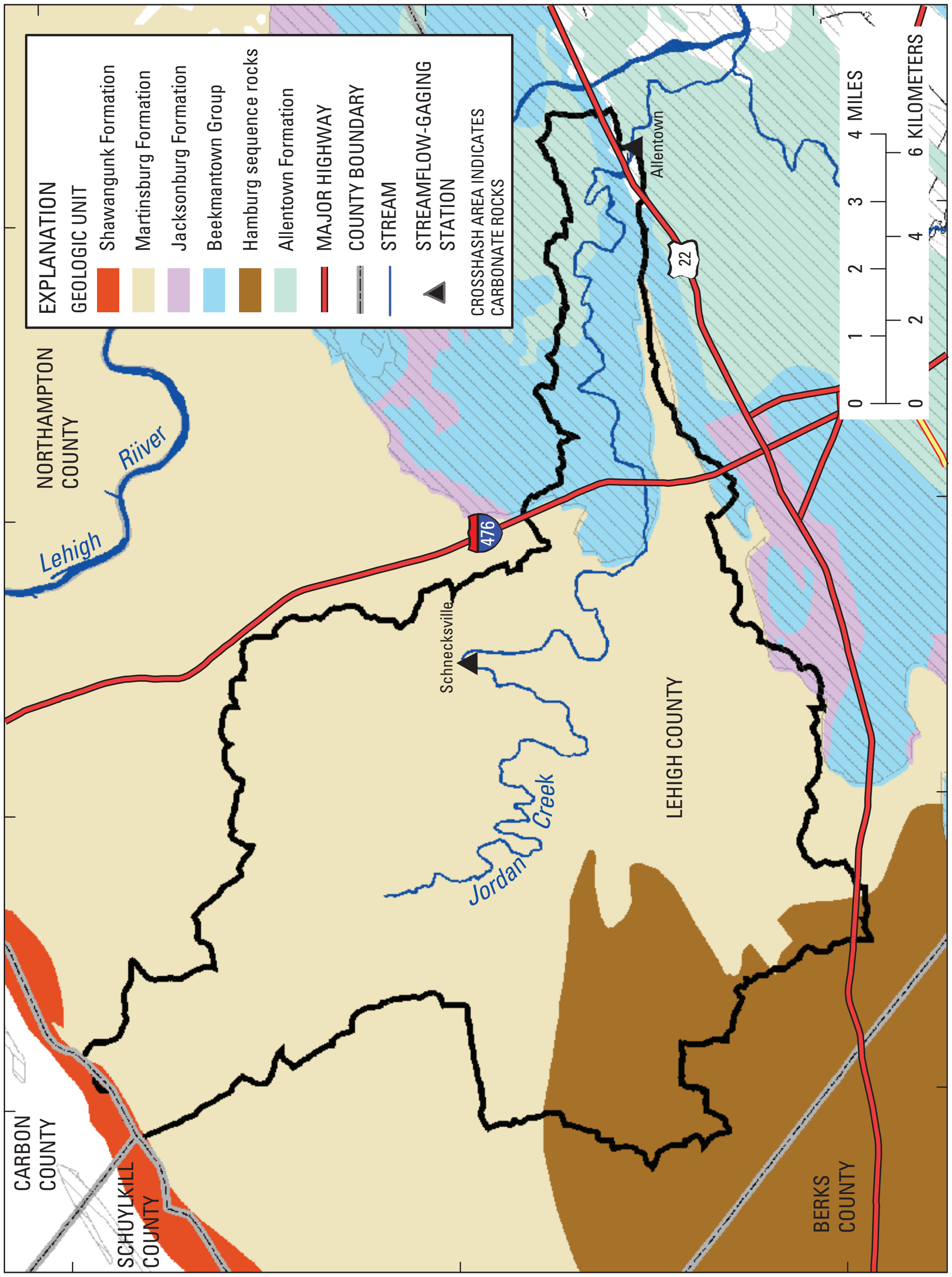
$$R = P - (ET + RO + \Delta S) \,, \qquad (1)$$

where:

- R is recharge, in inches,
- P is precipitation, in inches ,
- ET is evapotranspiration, in inches,
- RO is surface runoff, in inches, and
- ΔS is change in storage, in inches.

The water-budget method is attractive because it can be applied almost anywhere precipitation data are available. A major drawback of the method is that recharge is estimated as the residual term in an equation where the other budget terms usually are estimated with considerable error, which can result in large errors in the recharge estimate (Scanlon and others, 2002, p. 21). Thus, in this study, the results from the water-budget model were compared to the streamflow measured at streamflow-gaging stations and to the estimates of recharge and base flow derived from those streamflow records.

[1] The stratigraphic nomenclature used for geologic units in this report is that of the Pennsylvania Department of Conservation and Natural Resources, Bureau of Topographic and Geologic Survey and may not conform to that of the U.S. Geological Survey.



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

Figure 2. Generalized bedrock geology of the study area in Jordan Creek watershed, Lehigh County, Pa.

Description of the Water-Budget Model

The water-budget model used in this study is called the Hydrological Evaluation of Landfill Performance (HELP) model version 3.07 (Schroeder and others, 1994a). The HELP model is a physically based, water-budget computer program developed by the U.S. Army Waterways Experiment Station to compute the water budget of landfills. The model uses data on climate, soils, and vegetation with various algorithms to account for and route water inflow, outflow, and change in storage on a daily basis. HELP is a "quasi-two-dimensional" model that routes precipitation falling on the land to components of evapotranspiration, surface runoff, storage, and vertical percolation (recharge) for a layered soil column. The lateral movement of water as surface runoff is accounted for by an output from the model, but two-dimensional flow is not explicitly modeled. The model algorithms are described in detail by Schroeder and others (1994b), and limitations of the model are discussed by Berger (2000) and Hauser and others (2005).

The HELP model operates by computing for each day the free water available on the land surface as the sum of precipitation, snowmelt, and surface storage. Surface runoff is subtracted from the free water available, and surface evaporation and sublimation are computed from the remaining free water available. Any free water remaining is available for infiltration. The infiltration is routed through each soil layer, with the amount of infiltration diminished by processes of evaporation from the soil and plant transpiration. Vertical movement is computed with the Campbell (1974) equation for unsaturated flow and is distributed through the soil profile in time steps of 0.5 to 6 hours. Vertical percolation through the base of the deepest model layer is considered recharge.

Recharge estimates from HELP are probably best categorized as "potential" recharge because, as applied in this study, water is only routed through the base of model layer 5, representing the soil thickness or the maximum depth of evapotranspiration, whichever is deeper. Percolation through the base of model layer 5 is assumed to reach the water table and become ground-water recharge (fig. 3). If, in reality, the percolation does not reach the water table, actual recharge would be less than predicted by the water-budget model.

The HELP model was chosen because it is a well-documented, nonproprietary model requiring input parameters that can mostly be derived from available soils and land-cover datasets. Also, Risser and others (2005c) showed that mean percolation simulated by the HELP model compared closely to that measured from zero-tension lysimeters at an Agricultural Research Service (ARS) research site in Northumberland County, Pa., during 1994-2001. That result, however, may not have been typical, because Hauser and others (2005) reported that the HELP model substantially overestimated percolation collected by lysimeters at an ARS site in Ohio having similar climate and soils as the Jordan Creek watershed. The error was attributed to an underestimation of evapotranspiration by the HELP model. Also, Berger (2000) pointed out errors and limitations in the HELP model from his research in Germany.

Other water-budget models are available that could be used with a GIS to map the spatial variability of recharge. Examples of other models are EPIC (Mitchell and others, 1998), HYDRUS-1D (Vogel and others, 1996), and the deep percolation model of Bauer and Vaccaro (1987). Testing the applicability of these other models was beyond the scope of this study.

Automated Application of the Model

For this study, a simulation of recharge from the HELP model was required for each unique landscape unit. Because many landscape units were delineated, an automated 3-step procedure was developed to (1) format input datasets, (2) run the model, and (3) summarize the results. For each landscape unit, input files were required in a specified format that described the soil properties, evapotranspiration factors, and daily precipitation. Thus, a computer program was used to format the input files for the HELP model and assign the characteristics representing each landscape unit. After the input files were completed for all landscape units, another program was used to run water-budget simulations for each landscape unit and save the output. Finally, the simulations of recharge for each landscape unit, output by the water-budget model in separate files, were summarized to obtain a water budget for the study area.

Delineation of Landscape Units

Jordan Creek watershed was divided into small land parcels termed "landscape units" for this study. Landscape units were chosen such that many of the significant variables affecting ground-water recharge—soil type, slope, vegetation, and precipitation—would be similar within a landscape unit. Thus, the landscape units were identified by intersecting GIS datasets of soils, land use/land cover, and mean annual precipitation. The intersection of 58 soil mapping units, 6 general land-use/land-cover classes, and 5 precipitation zones resulted in the delineation of 577 unique landscape units in the Jordan Creek watershed. However, even with this large number of landscape units, considerable heterogeneity in physical properties exists within each landscape unit that may not be fully represented.

Soils

The spatial distribution and properties of soils in the Jordan Creek watershed were determined from the Soil Survey Geographic Database (SSURGO) for Lehigh County, Pa. (U.S. Department of Agriculture, 2004). SSURGO is a digital soil survey consisting of a georeferenced digital map at a scale of 1:63,360 and computerized attribute data. SSURGO is an update to the original Natural Resources Conservation Service

(NRCS) soil survey of Lehigh County (Carey and Yaworski, 1963). In the Jordan Creek watershed, 60 soil mapping units were identified in the SSURGO dataset (table 1 and fig. 4). To define landscape units, mapping units for open water and quarries were omitted, so only 58 soil mapping units were used. The mapping units represent 36 soil series on various slopes; the predominant soil series is the Berks-Weikert Complex, covering 67 percent of the Jordan Creek watershed.

Land Use/Land Cover

The spatial differences in land use/land cover in the Jordan Creek watershed were determined from the Pennsylvania Land Cover, 2000 (PALULC2000) dataset (The Pennsylvania State University, 2003). PALULC2000 is a statewide land-cover map updated from the Multi-Resolution Land Characteristics Consortium 1992 dataset (Vogelmann and others, 2001) by the use of satellite data and other ancillary data sources. The PALULC2000 dataset shows the distribution of 11 different land-use/land-cover classes within the Jordan Creek watershed that were generalized into 8 classes for this study (table 2 and fig. 5): crops (43.6 percent), forest (26.6 percent), pasture (18.6 percent), low-density urban (8.0 percent), high-density urban (1.9 percent), water (0.9 percent), woody wetland (0.2 percent), and emergent wetland (0.2 percent). The generalized land-use/land-cover class “water” was excluded from the water-budget analysis.

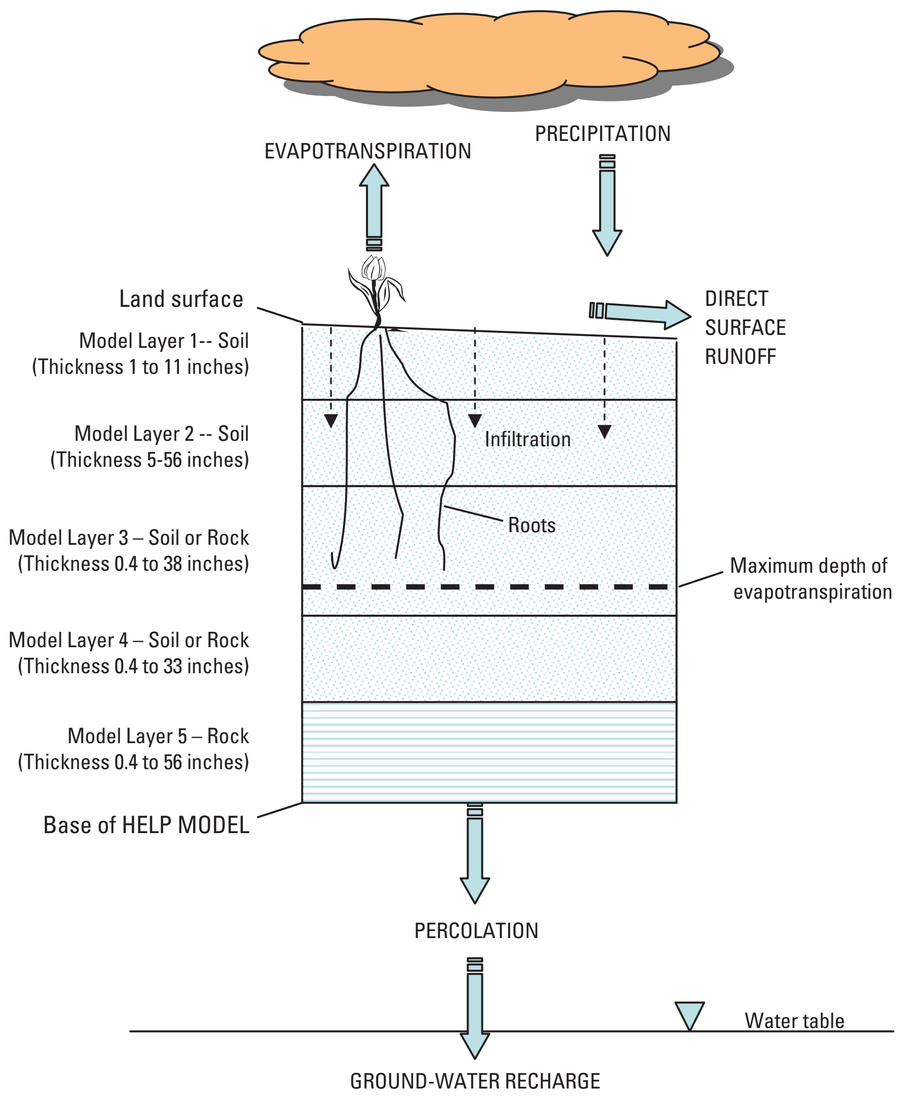
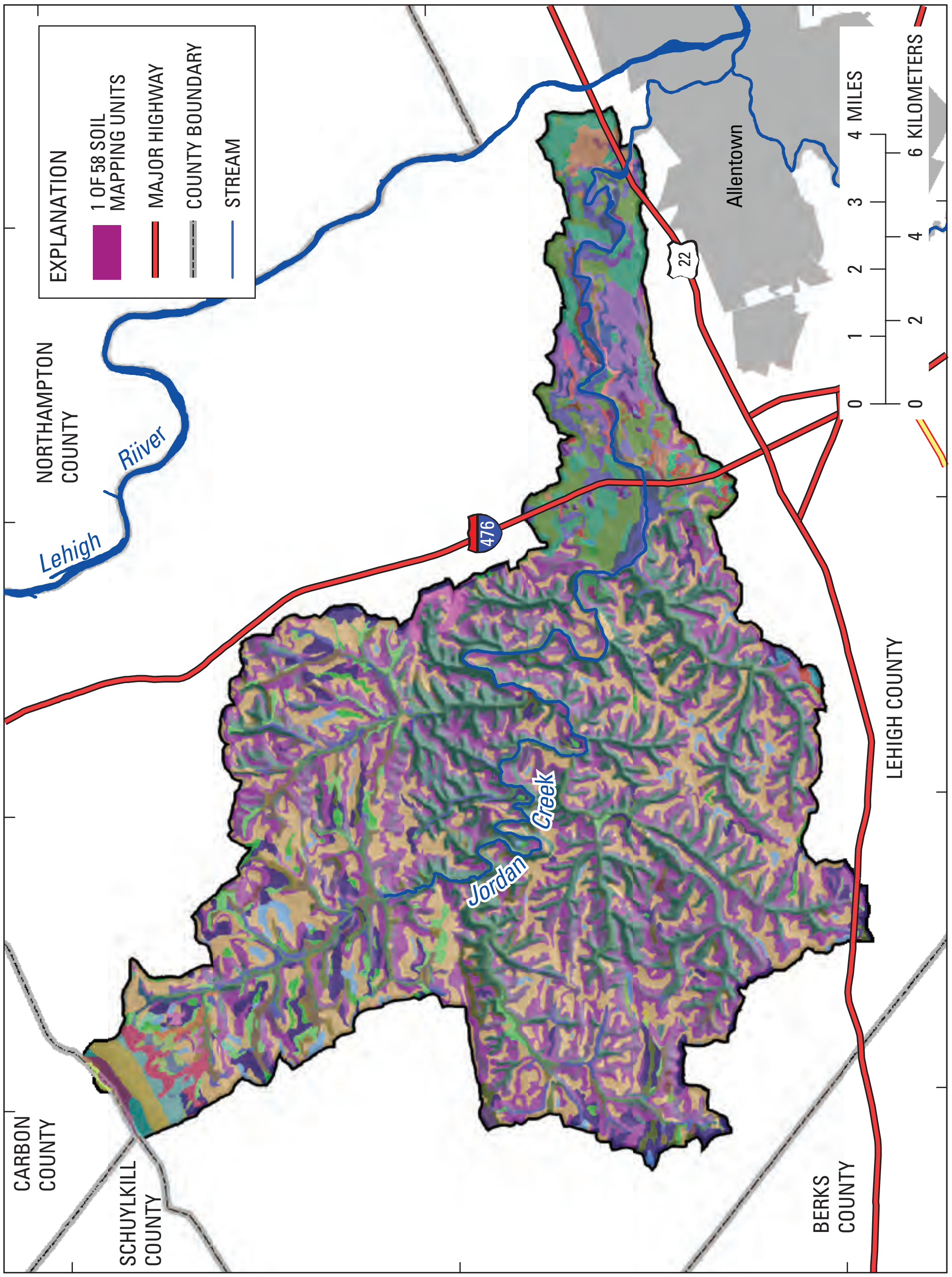


Figure 3. Schematic representation of water-budget terms and layers used in the water-budget model.



Base from U.S. Geological Survey digital line data, 2001, 1:100,000
Soils from U.S. Depoartment of Agriculture (2004)

Figure 4. Distribution of soil mapping units from SSURGO soils dataset within Jordan Creek watershed, Lehigh County, Pa.

Table 1. Soil mapping units within Jordan Creek watershed, Lehigh County, Pa.

[—, not available]

Soil mapping unit	Soil association	Percent slope	Area, in square miles	Area, as percent of study area
AfA	Allentown silt loam	0 - 3	0.09	0.11
AfB	Allentown silt loam	3 - 8	.06	.08
AnB	Andover-Buchanan gravelly loams	3 - 8	.07	.10
AoB	Andover-Buchanan gravelly loams	0 - 8	.08	.11
ArB	Arendtsville gravelly silt loam	3 - 8	.02	.02
BfA	Bedington-Berks complex	0 - 3	.68	.90
BfB	Bedington-Berks complex	3 - 8	3.24	4.26
BfC	Bedington-Berks complex	8 - 15	.70	.92
BhD	Berks-Bedington complex	15 - 25	.11	.15
BkA	Berks-Weikert complex	0 - 3	.94	1.23
BkB	Berks-Weikert complex	3 - 8	14.86	19.49
BkC	Berks-Weikert complex	8 - 15	14.71	19.30
BkD	Berks-Weikert complex	15 - 25	8.22	10.78
BkF	Berks-Weikert complex	25 - 60	12.51	16.41
BmA	Birdsboro silt loam	0 - 3	.04	.06
BmB	Birdsboro silt loam	3 - 8	.12	.16
BtA	Brinkerton-Comly silt loams	0 - 3	1.06	1.39
BtB	Brinkerton-Comly silt loams	3 - 8	.98	1.29
BuB	Buchanan gravelly loam	3 - 8	.16	.21
BvB	Buchanan gravelly loam	0 - 8	.41	.54
CaB	Calvin-Klinesville channery silt loams	3 - 8	.06	.08
CaC	Calvin-Klinesville channery silt loams	8 - 15	.02	.02
CaD	Calvin-Klinesville channery silt loams	15 - 25	.04	.06
CmA	Clarksburg silt loam	0 - 3	.07	.09
CmB	Clarksburg silt loam	3 - 8	.22	.29
CpA	Comly silt loam	0 - 3	.30	.39
CpB	Comly silt loam	3 - 8	1.32	1.74
DbA	Duffield silt loam	0 - 3	.05	.06
DbB	Duffield silt loam	3 - 8	1.02	1.34
DfC	Duffield-Ryder silt loams	8 - 15	.30	.39
DfD	Duffield-Ryder silt loams	15 - 25	.19	.24
Fb	Fluvaquents	1	.06	.08
HeB	Hazleton very channery loam	0 - 8	.04	.05
HeD	Hazleton very channery loam	8 - 25	.02	.03
HeF	Hazleton very channery loam	25 - 60	.18	.24
HgF	Hazleton-Rubble land complex	25 - 60	.13	.17
Ho	Holly silt loam	2	2.34	3.07
LaB	Laidig gravelly loam	3 - 8	.10	.13
LbB	Laidig very gravelly loam	0 - 8	.29	.38
LbD	Laidig very gravelly loam	8 - 25	.50	.66
LdF	Laidig-Rubble land complex	25 - 55	.01	.01
Lv	Linden loam	2	.44	.57
Me	Middlebury silt loam	6	.82	1.07
MgB	Monongahela silt loam	3 - 8	.03	.03
PeB	Penn Channery silt loam	3 - 8	0.01	0.01
Qu	Quarries	—	.09	.12

Table 1. Soil mapping units within Jordan Creek watershed, Lehigh County, Pa.—Continued

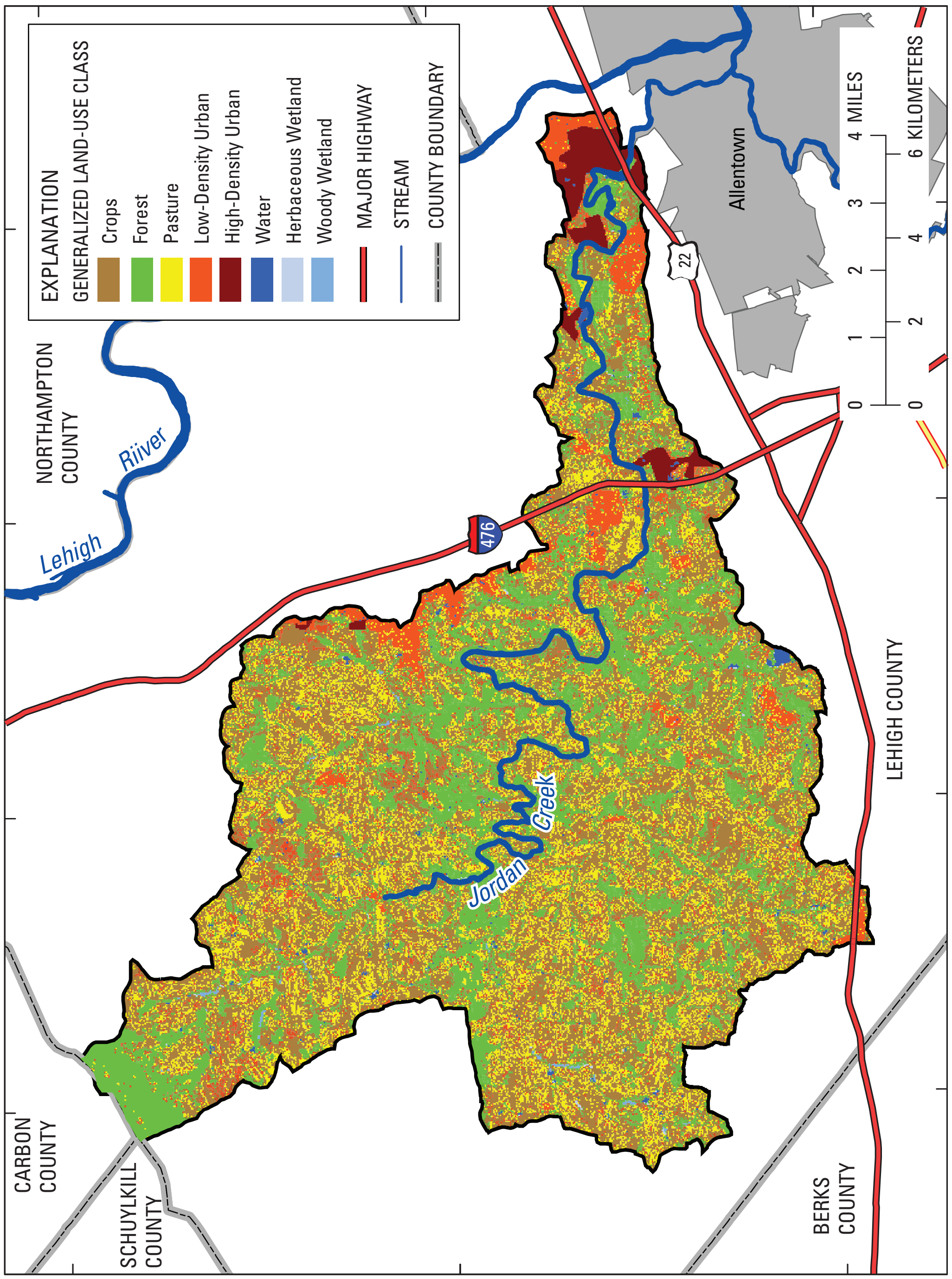
[—, not available]

Soil mapping unit	Soil association	Percent slope	Area, in square miles	Area, as percent of study area
ThA	Thorndale-Penlaw silt loams	0 - 3	.18	.24
Ua	Udorthents	15	.25	.33
UgB	Urban land	0 - 8	.42	.56
UgC	Urban land	8 - 15	.07	.09
UkB	Urban land-Berks complex	0 - 8	.27	.36
UmB	Urban land-Duffield complex	0 - 8	1.84	2.41
UmD	Urban land-Duffield complex	8 - 15	.19	.25
W	Water	—	.43	.57
WaA	Washington silt loam	0 - 3	.08	.10
WaB	Washington silt loam	8 - 15	2.31	3.04
WaC	Washington silt loam	8 - 15	1.06	1.39
WaD	Washington silt loam	15 - 25	.22	.29
WeB	Weikert-Berks complex	3 - 8	.29	.39
WeD	Weikert-Berks complex	15 - 25	.93	1.22
			76.24	100.00

Table 2. Generalized land-use/land-cover classes from the PALULC2000[1] dataset within the Jordan Creek watershed, Lehigh County, Pa.

Generalized land-use/land-cover classes for this study	Land-use/land-cover classification from PALULC2000 dataset	Area, in square miles	Area, as percent of study area
Crops	Row crops	33.2	43.6
Forest	Deciduous forest	17.1	22.4
Forest	Coniferous forest	2.5	3.3
Forest	Mixed forest	.7	.9
Pasture	Hay pasture	14.2	18.6
Low-density urban	Low-density urban	3.6	4.7
Low-density urban	Transitional	2.5	3.3
High-density urban	High-density urban	1.5	1.9
Unused	Water	.7	.9
Woody wetland	Woody wetland	.1	.2
Herbaceous wetland	Emergent herbaceous wetland	.1	.2
		76.2	100

[1]The Pennsylvania State University, 2003.



Base from U.S. Geological Survey digital line data, 2001, 1:100,000
Land use from The Pennsylvania State University (2003)

Figure 5. Distribution of generalized land-use/land-cover classes from the PALULC2000 dataset within Jordan Creek watershed, Lehigh County, Pa.

Precipitation

Long-term precipitation has been monitored at one location (Claussville) within the Jordan Creek watershed (fig. 6). During the period 1951-2000, precipitation at Claussville averaged 44.68 in/yr, as determined from reported data (U.S. Department of Commerce, 2007) and from estimates of precipitation for periods of missing data determined by regression from nearby precipitation stations using a method described by Hay and others (2000). To determine if the precipitation at Claussville is representative of the entire watershed, mean annual precipitation from the five nearest stations surrounding the basin was determined for 1951-2000. The location of each station was mapped and an area of Jordan Creek watershed was assigned to the precipitation value of each nearby station (fig. 6) on the basis of the Thiessen polygon method (Gray, 1973). This resulted in five precipitation zones, each of which was assigned a value representing the ratio of mean annual precipitation at the station in that zone to the precipitation at Claussville during 1951-2000. The ratios for the watershed range from 0.92 to 1.06 and are expressed as percentages in figure 6.

Model Parameters for Jordan Creek Watershed

For each landscape unit, data describing the climate, vegetation, soils, and runoff characteristics were needed to compute recharge using the water-budget model. The data used to compute recharge for the Jordan Creek watershed are described in this section. Some of the data values are used as constants to represent parameters in the water-budget model for all landscape units; other data values differ among landscape units because of differences in climate, vegetation, and soil type. Values of parameters used in the water-budget model for the 577 landscape units in the Jordan Creek watershed are listed in the appendix.

Climate Data

Climate data used to estimate recharge in the model for the Jordan Creek watershed were precipitation, temperature, solar radiation, wind speed, and relative humidity. Only values for precipitation were varied among landscape units; the other climate data were assumed to be constant throughout the Jordan Creek watershed.

Precipitation

Values of daily precipitation are needed to estimate recharge by the water-budget model. A dataset for daily precipitation during 1951-2000 was compiled to represent precipitation near the center of the Jordan Creek watershed by use of measured precipitation from Claussville (U.S. Department of Commerce, 2007). Precipitation values on days with missing data were estimated by multiple-linear regression using data from surrounding precipitation stations and the latitude, longitude, and altitude of each station using a method developed by Hay and others (2000).

For each landscape unit, a dataset of daily precipitation was derived by adjusting each daily value from the station at Claussville by a constant amount to account for variations in precipitation defined by the five zones in the Jordan Creek watershed. Mean annual precipitation at Claussville was 44.68 in/yr for 1951-2000. The adjustment factors ranged from 92 to 106 percent of the precipitation at Claussville (fig. 6). Precipitation applied to the various landscape units ranged from 41.1 to 47.3 in/yr. The mean precipitation for the study area, weighted by the area of the precipitation zones, was 44.8 in/yr for 1951-2000.

Temperature

Values of daily mean temperature are used in the water-budget model to determine the state of the precipitation (rain or snow) and are required as input for equations used to compute evapotranspiration. Because the station at Claussville does not report temperature, a dataset for daily mean temperature at Allentown during 1951-2000 was compiled to represent temperature of all landscape units in the Jordan Creek watershed. Daily mean temperature was computed as the mean of the daily maximum and minimum temperatures recorded at Allentown (U.S. Department of Commerce, 2007). Missing data for the station at Allentown were estimated by multiple-linear regression using available data at surrounding temperature stations and their latitude, longitude, and altitude using a method developed by Hay and others (2000). The mean annual temperature at Allentown seemed to be a reasonable representation for the basin, given values for nearby climate stations outside of the watershed. For the period of concurrent record during 1971-2000, mean annual temperature at Allentown was 50.6 degrees Fahrenheit compared to 51.9 degrees at Palmerton, 49.2 degrees at the Rodale Research Center, and 48.2 degrees at Beltsville Dam.

In addition to daily mean temperature, data for the mean monthly temperature is used in some of the algorithms for estimating seasonal variations in vegetative growth (Arnold and others, 1989) that are used to compute transpiration from plants in the water-budget model. The mean monthly temperatures from the meteorological station at Allentown from 1951 to 2000 were used to represent the Jordan Creek watershed (table 3).

Solar Radiation

Solar radiation is required in the equations used to compute evapotranspiration. A dataset of daily total global solar radiation was generated synthetically by the HELP model

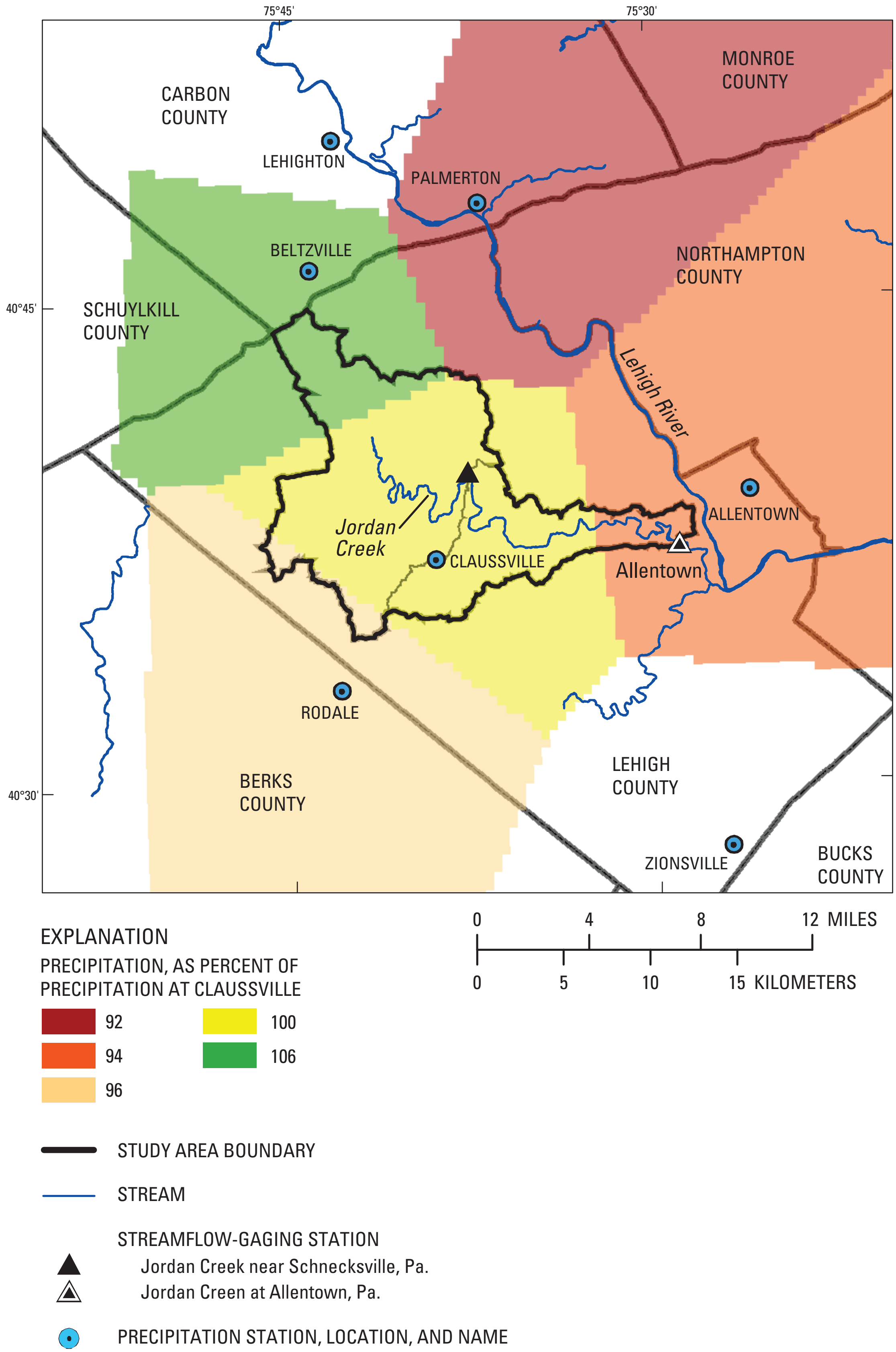


Figure 6. Precipitation ratios computed by the Thiessen method within the Jordan Creek watershed, Lehigh County, Pa.

Table 3. Mean monthly temperature at Allentown, 1951-2000, Lehigh County, Pa.

Month	Mean temperature, degrees Fahrenheit
Jan	28.0
Feb	30.4
Mar	38.8
April	50.0
May	60.3
June	69.4
July	74.1
Aug	72.1
Sept	64.6
Oct	53.6
Nov	42.8
Dec	32.0

from the **W**eather **Gen**erator (WGEN) model of Richardson and Wright (1984). The generated values of solar radiation are computed as a function of the daily mean precipitation at Claussville, using the statistical characteristics of the historic solar radiation at Pittsburgh from the HELP model and adjusting for basin latitude. The latitude of the Claussville precipitation station, 40.62 degrees north latitude, was used because it is about in the center of the Jordan Creek watershed (fig. 1). The daily values of synthesized solar radiation were assumed to represent the solar radiation received by all landscape units in the Jordan Creek watershed.

Wind Speed

Mean annual wind speed is used by the HELP model to simulate evapotranspiration. The wind speed for the entire Jordan Creek watershed was assumed to be equal to that recorded at the meteorological station at Allentown. Mean annual wind speed at Allentown was 9 mi/h during 1949-98 (Northeast Regional Climate Center, 2007).

Relative Humidity

Relative humidity is used by the HELP model to simulate evapotranspiration. The average quarterly value of relative humidity for the entire Jordan Creek watershed was assumed to be equal to that recorded at the weather station at Allentown. Quarterly values of relative humidity were 67 percent (January-March), 64 percent (April-June), 70 percent (July-Sept), and 71 percent (October-December) at Allentown during 1949-98 (Northeast Regional Climate Center, 2007).

Vegetation Data

Vegetation data are required to estimate evapotranspiration and surface runoff. A uniform value of growing-season length was used to represent all landscape units in the Jordan Creek watershed, but data for maximum leaf-area index (LAI) and evaporative-zone depth were specified for each landscape unit, depending on its land-use/land-cover class and soil characteristics.

Growing Season

The start and end dates of the growing season are used in the vegetative growth algorithms in the water-budget model. For the entire Jordan Creek watershed, the length of the growing season was assumed to be equal to the length of the growing season at Allentown, Pa. For the period 1948-98 at Allentown, the average date of last freeze was April 20 (Julian day 110), and the average date of first freeze was October 18 (Julian day 291); the average length of the growing season was 181 days (The Pennsylvania State Climatologist, 2007).

Leaf-Area Index

Leaf-area index (LAI) is a measure of canopy foliage, expressed as a dimensionless ratio of actively transpiring leaf area to the land surface over which the foliage extends. The maximum LAI for a particular land cover is an input used by the HELP model to compute evapotranspiration. Values of LAI are difficult to determine for a watershed area. Values for maximum LAI from 1.5 to 6 were assigned to the land-cover classes in the Jordan Creek watershed (table 4). The values were loosely derived from global average values of LAI observations by Asner and others (2003) and from recommendations in the HELP documentation (Schroeder and others, 1994b).

Table 4. Maximum values of leaf-area index assigned for land-use/land-cover classes in the Jordan Creek watershed, Lehigh County, Pa.

General land-use/ land-cover class	Maximum leaf-area index
Water	0
Low-density urban	2.5
High-density urban	1.5
Pasture	3.0
Crops	4.0
Forest	5.0
Woody wetlands	6.0
Herbaceous wetlands	6.0

Evaporative-Zone Depth

Evaporative-zone depth is the maximum depth from which water can be removed by evapotranspiration. In the HELP model, the evaporative-zone depth determines the soil layers from which water can be lost by evapotranspiration, affecting the quantity of water available for recharge. The evaporative-zone depth for the Jordan Creek watershed was estimated to be 1.1 times the maximum rooting depths given by Charles and others (1993, table 2) for differing combinations of vegetation and soil texture. The maximum depth from which water can be removed by evapotranspiration can exceed the maximum rooting depth of vegetation (Schroeder and others, 1994a, p. 10) depending on soil type, but the extent to which this occurs is not known, so the factor of 1.1 was arbitrarily chosen.

To use this method, the vegetation for each generalized land-cover class in the Jordan Creek watershed was divided into the four rooting classes used by Charles and others (1993, table 2)—shallow-rooted, moderately deep-rooted, deep-rooted, or mature forest; soil texture was obtained from the SSURGO dataset (table 5). Land cover classified as high-density urban and low-density urban was assumed to have turf grass with moderately deep roots, and the vegetation on herbaceous wetlands was assumed to be shallow rooted. Soil textures were grouped as either silt loam or clay loam. Values of evaporative-zone depth assigned to landscape units in the Jordan Creek watershed ranged from 1.46 to 7.33 ft (table 5).

Soils Data

The SSURGO soil dataset was used to determine values of the following properties for each of the five model layers for each landscape unit—layer thickness, vertical hydraulic conductivity, porosity, wilting point, and field capacity. These properties are listed for each of the 577 landscape units in the appendix.

Layer Thickness

Each landscape unit was characterized with five vertical layers for use in the water-budget model (fig. 3). The thickness of each layer was determined from the soil-layer thickness for the soil series of that landscape unit reported in the SSURGO soils dataset. Layer thickness ranged from 0.4 to 69 in., and total thickness of the five-layer soil profile ranged from 43 to 87 in. for the 577 landscape units (appendix). For landscape units where fewer than five layers were reported in the SSURGO soils dataset, the layers were assigned a minimal thickness of 0.4 in. and attributed with the same values as the overlying layer; thus, their presence had little effect on the storage and infiltration of water. In cases where the total thickness of the soil layers reported in the SSURGO soils dataset was less than the estimated thickness for the evaporative-zone depth, the thickness of model layer 5 was increased so that the total thickness of the five model layers would equal the evaporative-zone depth. This was done because it is likely that roots penetrate into the friable, highly weathered rock beneath the soil.

Vertical Hydraulic Conductivity

A saturated vertical hydraulic-conductivity value ranging from 0.3 to 26 ft/d was assigned for each layer of each landscape unit on the basis of values available from the SSURGO soils dataset for the Jordan Creek watershed (see appendix). The saturated vertical hydraulic conductivity is used to quantify the ability of water to flow when the void spaces in the soil are filled with water. Saturated vertical hydraulic conductivity also is used by the water-budget model to compute the unsaturated vertical hydraulic conductivity using an equation reported by Campbell (1974).

Porosity

Porosity ranging from 0.358 to 0.547 was estimated for each of the five layers in each landscape unit of the Jordan

Table 5. Maximum depth of evapotranspiration assigned for land-cover classes and soil textures in the Jordan Creek watershed, Lehigh County, Pa.

Vegetation type	Generalized land-use/ land-cover class	Maximum depth of evapotranspiration, in feet	
		Silt loam soil texture	Clay loam soil texture
Shallow rooted	Herbaceous wetlands	2.29	1.46
	Crop (corn and small grain)	3.66	2.94
Moderately deep rooted	High-density urban	3.66	2.94
	Low-density urban	3.66	2.94
Deep rooted	Pasture	4.59	3.66
Mature forest	Forest	7.33	5.86
	Woody wetlands	7.33	5.86

Creek watershed (see appendix). Porosity was computed according to Hillel (1982, eq. 2.13) using the bulk density of the soil reported in the SSURGO soils dataset as:

$$\Phi = 1 - (\rho_b / \rho_s) \quad (2)$$

where:

Φ is the porosity (dimensionless ratio),

ρ_b is the dry bulk density of the soil, in pounds per cubic foot, from the SSURGO soils dataset, and

ρ_s is the density of the solid particles, in pounds per cubic foot.

Bulk density for soils in the Jordan Creek watershed ranged from 75 to 106 lb/ft^3. Where not specified in the SSURGO soils dataset, bulk density was assumed to equal 81 lb/ft^3. The density of solid particles was assumed to be 165 lb/ft^3. For weathered bedrock layers not included in the SSURGO soils dataset, a porosity of 0.07 was assigned.

Wilting Point

Wilting-point estimates for landscape units in the Jordan Creek watershed ranged from 0.024 to 0.251 (see appendix). Wilting point is the minimum soil-moisture content at which a plant wilts. Operationally, wilting point is defined as the water content at −15 bars of suction pressure. Wilting point was estimated for each layer of each landscape unit from values given in the HELP documentation (Schroeder and others, 1994b, p. 19) on the basis of the soil texture of each layer from the SSURGO soils dataset. For weathered bedrock layers not included in the SSURGO soils dataset, a wilting point of 0.01 was assigned.

Field Capacity

Field-capacity estimates for soils in the Jordan Creek watershed ranged from 0.09 to 0.38 (see appendix). Field capacity was estimated for each layer of each landscape unit as the wilting point plus the available water capacity. Available water capacity is the quantity of water available between the wilting point and field capacity of a soil. Available water capacity was given in the SSURGO soils dataset. In the Jordan Creek watershed, available water capacity from the SSURGO soils dataset ranged from 0.06 to 0.22. For weathered bedrock layers not included in the SSURGO soils dataset, a field-capacity value of 0.02 was assigned.

Runoff Data

The water-budget model computes surface runoff by use of the Soil Conservation Service (SCS) curve-number method (U.S. Department of Agriculture, 1985). Surface runoff is that component of precipitation from a storm that moves over the soil surface. Using this method, surface runoff is computed from a rainfall-runoff equation developed from data for storms on small watersheds. The runoff-curve number "CN" in the equation determines the proportion of surface runoff for a given amount of precipitation in a 24-hour period. The method does not account for rainfall intensity or duration.

The runoff-curve number can vary between 0 and 100; higher numbers generate greater amounts of surface runoff. Runoff-curve numbers were assigned to each landscape unit (appendix) as described in SCS Technical Release 55 (U.S. Department of Agriculture, 1986) on the basis of their hydrologic soil group (A, B, C, or D) from the SSURGO soils dataset and land-cover class from the PALULC2000 dataset. Determining a runoff-curve number on the basis of generalized land-cover classes results in a generalized runoff-curve number that probably accurately represents only part of the landscape unit, because the runoff-curve number depends on the hydrologic condition of the cover (e.g. percent of residue cover on land surface) and treatment (e.g. contoured or terraced), which vary by farm field within the landscape unit. Those curve numbers were then adjusted for slope by the equation given in the HELP model documentation (Schroeder and others, 1994b, equation 34). Adjusting for slope caused the runoff-curve number to be increased for slopes greater than 8 percent. Runoff-curve numbers assigned to landscape units in the Jordan Creek watershed ranged from 55 for forests to 95 for high-density urban areas (table 6). Values of 98 were assigned to all wetlands, based on the assumption that most water would run off.

Recharge Estimates

The mean annual recharge was 12.3 in. on the basis of the water-budget model for the Jordan Creek watershed for 1951-2000. Precipitation, evapotranspiration, surface runoff, percolation (recharge), and change in storage were simulated for each of the 577 landscape units on a daily basis, and the daily values were used to compute mean annual rates for 1951-2000

Table 6. Maximum, minimum, and mean values of runoff-curve number by land-use/land-cover class for Jordan Creek watershed, Lehigh County, Pa.

Generalized land-use/ land-cover class for this study	Runoff-curve number for land-use/land-cover class		
	Maximum	Minimum	Mean
Forest	78	55	66
Pasture	81	61	71
Res-LO (low-density residential)	85	70	77
Crops	85	74	80
Res-HI (high-density residential)	95	90	92
Wetlands (woods or plants)	98	98	98

for each landscape unit. The water budget for each landscape unit was then weighted by the percentage of that landscape in the watershed, and the weighted values were summed to determine the water budget of the Jordan Creek watershed for 1951-2000 (table 7).

Spatial Distribution of Recharge

Simulated values of recharge during 1951-2000 ranged from 0.11 in/yr for a wetland landscape to 17.1 in/yr for an upland soil in the Jordan Creek watershed. Recharge within the watershed differed spatially because of differences in local climate, physiography, soils, and land cover. These major factors were incorporated in the water-budget model for the 577 different landscape units. The range of recharge values simulated by the water-budget model for all landscape units is shown in a cumulative frequency graph (fig. 7). Simulated mean annual recharge for 73 percent of the landscape units ranged from 9 to 14 in.

The spatial distribution of recharge simulated by the water-budget model is shown in figure 8. Areas of large and small recharge are interspersed throughout the basin. Relatively contiguous areas mapped as having the greatest recharge (blue shading in figure 8) tend to be mostly forested landscape units along valley sides. Scattered areas of high recharge also occur in areas of pasture with thin soils. Areas with lowest recharge rates (red shading in figure 8) are wetlands along streams and urban areas near Allentown. The effect of the zones of differing precipitation also can be seen in the simulated recharge rates. The zones of lower than average precipitation in the east and southwest edges of Jordan Creek watershed (fig. 6) correspond to areas of lower than average

Table 7. Water budget for 1951-2000 computed using the water-budget model HELP for Jordan Creek watershed, Lehigh County, Pa.

Water-budget term		Mean annual inflow or outflow, in inches	Mean annual inflow or outflow, as percentage of total
Inflow	Precipitation	44.8	100
	Evapotranspiration	28.2	63
Outflow	Recharge	12.3	27
	Surface runoff	4.3	10

recharge shown in figure 8. The area of greatest precipitation in the northern part of the watershed (fig. 6) tends to have landscapes with greater than average recharge.

Factors Affecting Simulated Recharge

The effect of land-use/land-cover class on simulated mean annual recharge rates during 1951-2000 is shown in figure 9. Mean annual recharge rates for crop, forest, pasture, and low-density urban land-use/land-cover classes (11.2 to 12.2 in/yr) were similar. Substantially less recharge was simulated for high-density urban (6.8 in/yr), herbaceous wetlands (2.5 in/yr), and forested wetlands (1.3 in/yr). All mean-annual recharge values less than 4 in/yr were for wetland landscapes, and values from 4 to 7 in/yr were all for high-density urban landscapes.

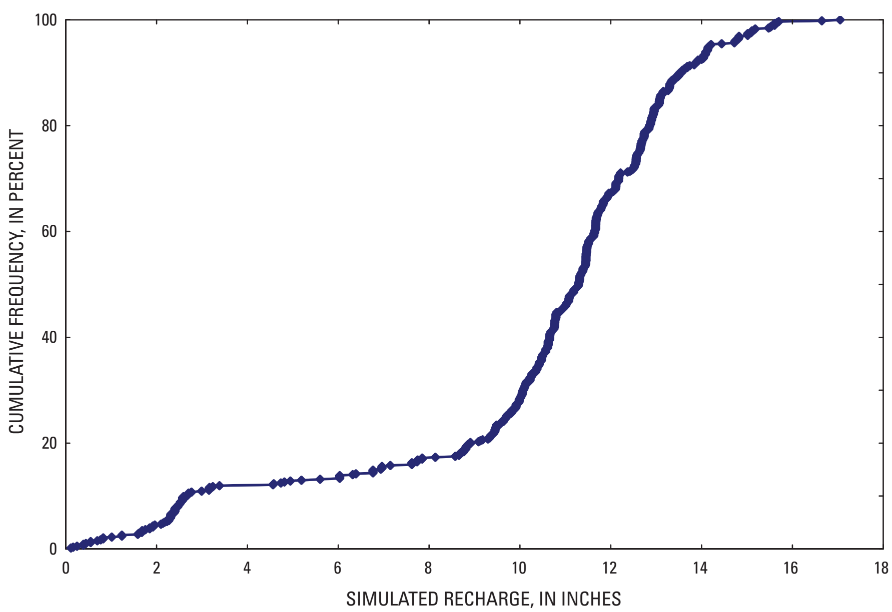


Figure 7. Cumulative frequency distribution of mean annual recharge during 1951-2000 simulated for 577 landscape units in the Jordan Creek watershed, Lehigh County, Pa.

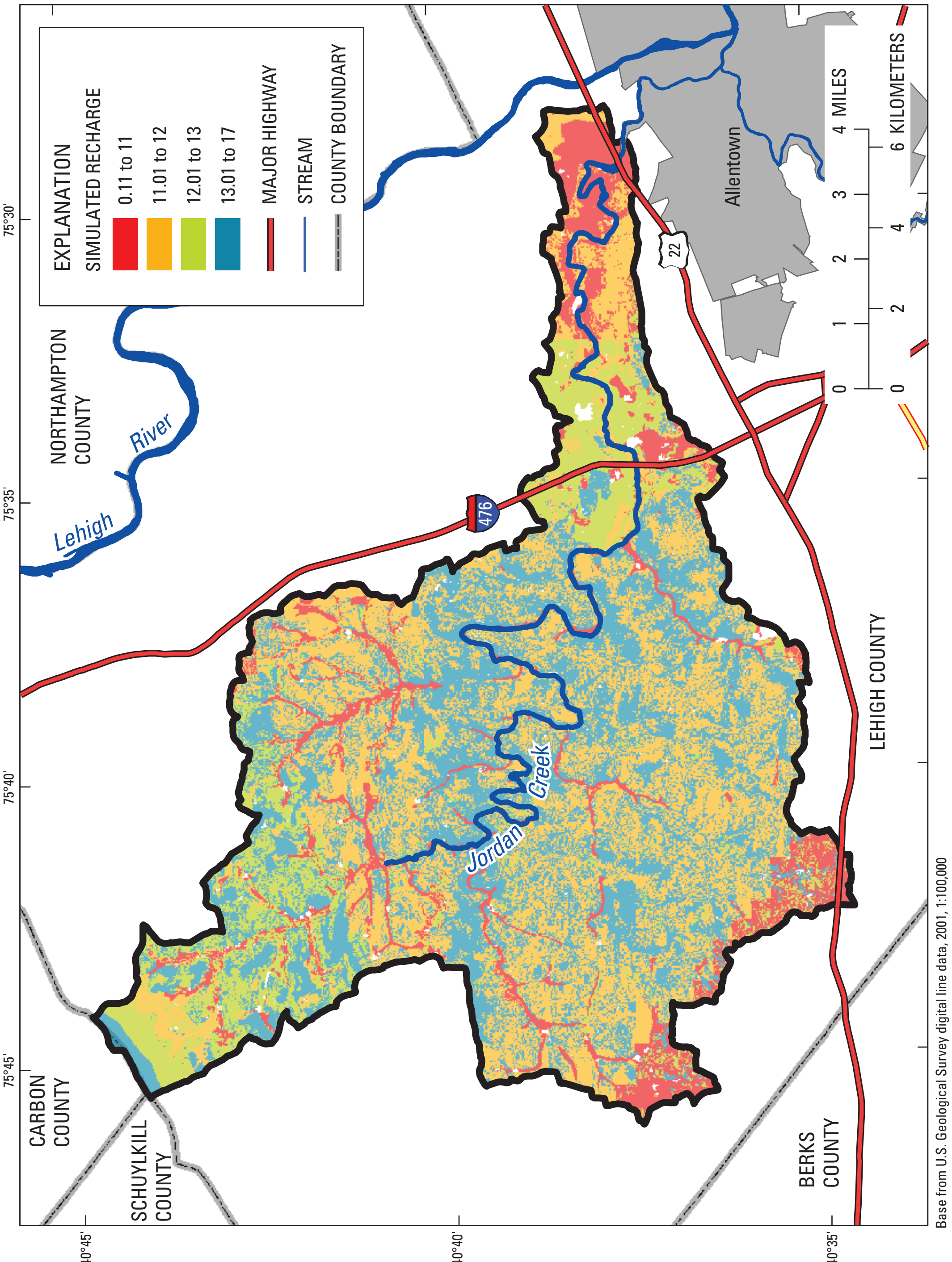


Figure 8. Spatial distribution of simulated mean annual recharge during 1951-2000 within the Jordan Creek watershed, Lehigh County, Pa.

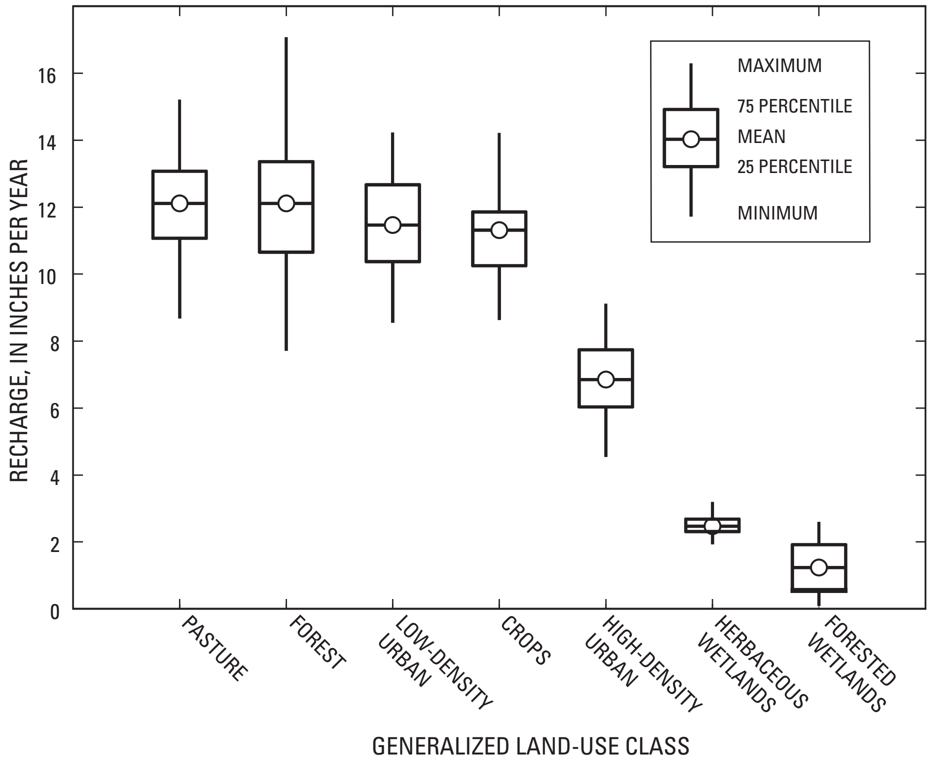
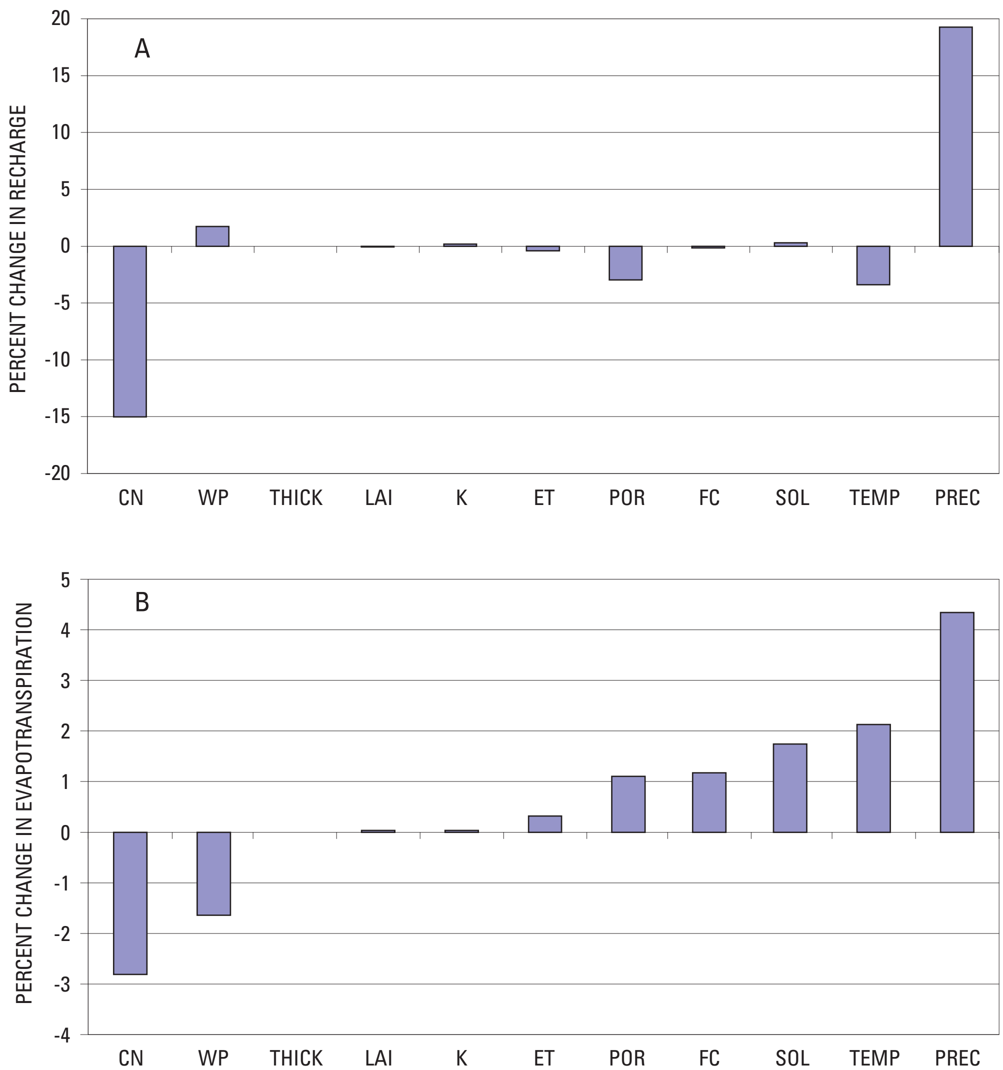


Figure 9. Mean and variability of simulated mean annual recharge during 1951-2000 by land-use/land-cover class in Jordan Creek watershed, Lehigh County, Pa.

Mean annual recharge estimates for the crop, forest, pasture, and low-density urban land-use/land-cover classes are similar because these landscapes are on the same types of soil and receive the same range of precipitation. The differing land-use/land-cover classes mostly affect the model input parameters of leaf-area index, runoff-curve number, and maximum depth of evapotranspiration. Recharge simulated by the water-budget model is not sensitive to LAI, and values of runoff-curve number and maximum depth of evapotranspiration tended to be offsetting. For example, values of runoff-curve number assigned to forested lands generally were smaller than for other land-use/land-cover classes (causing less runoff and more recharge), but the maximum depth of evapotranspiration assigned to forest lands was larger than for other land-use/land-cover classes (causing more evapotranspiration and less recharge). The smaller simulated mean annual recharge rates for high-density urban (6.8 in.) and wetland land-use/land-cover classes (2.5 and 1.3 in.) were caused by the large values of runoff-curve numbers (greater than 90) assigned to those classes (table 6).

The small simulated values of recharge for wetlands were predetermined by the large runoff-curve number of 98 specified for wetlands (table 6), causing nearly all water to run off. There was no guidance in SCS Technical Release 55 (U.S. Department of Agriculture, 1986) for estimating the runoff-curve number for wetlands, so a judgment was made that runoff from wetlands would be a large percentage of precipitation. This certainly is not realistic for all wetlands; some wetlands act as areas of ground-water discharge and some as areas of recharge. Choosing reasonable model parameters to characterize wetlands is a problem with using the water-budget approach.

The sensitivity of the mean annual recharge, simulated by the water-budget model for Jordan Creek watershed as a whole during 1951-2000, to changes in selected input parameters was computed (fig. 10A). The analysis shows the percentage change in recharge for the watershed caused by an increase of 10 percent in individual model parameters. Simulated recharge is most sensitive to changes in precipitation and the runoff-curve number (CN). A 10-percent increase in precipitation caused a 19-percent increase in recharge, and a 10-percent increase in runoff-curve number caused a 15-percent decrease in recharge. The sensitivity analysis shows the importance of accurate precipitation data for estimating recharge. In this study, variability in precipitation measured at the weather stations was incorporated by dividing the watershed into five zones of differing precipitation by use of the Thiessen polygon method. However, given the large sensitivity of simulated recharge to the amount of precipitation, a method to distribute precipitation that produces a smooth change of precipitation and accounts for altitude (orographic effects) would probably improve the recharge estimates. The large sensitivity of the runoff-curve number (fig. 10A) emphasizes the importance of making the best possible estimate of this parameter from



CN is runoff-curve number
WP is wilting point
THICK is total layer thickness
LAI is maximum leaf-area index
K is saturated vertical hydraulic conductivity
ET is evapotranspiration
POR is porosity
FC is field capacity
SOL is total solar radiation
TEMP is temperature
PREC is precipitation

Figure 10. Sensitivity of (A) mean annual recharge simulated by the water-budget model, and (B) mean annual evapotranspiration for the Jordan Creek watershed during 1951-2000, given a 10-percent increase in selected input parameters.

the guidance in SCS Technical Release 55 (U.S. Department of Agriculture, 1986). This parameter controls the amount of available water that runs off relative to that which infiltrates.

The sensitivity analysis indicates that a 10-percent increase of porosity and mean annual temperature has an effect on recharge simulated by the model (fig. 10A). An increase in porosity provides more storage in the root zone, allowing greater losses of water to transpiration and less water available for recharge. An increase in temperature also causes more evapotranspiration and decreases water available for recharge. The effect of temperature, however, is somewhat overstated in the sensitivity analysis, because the mean annual temperature varies in the watershed less than the 10 percent used in the sensitivity analysis. Although the assumption that mean-annual temperature for all landscape units throughout the basin was equal to the temperature recorded at Allentown might be a source of error, the mean annual temperature from nearby climate stations surrounding the watershed ranged from only 2.6 percent greater to 4.7 percent lower than at Allentown.

Changes in some of the parameters had little effect on the mean annual recharge of the basin. LAI is an example of a parameter that is difficult to estimate but seems to have little effect on simulated recharge. Some caution, however, is needed in interpreting the sensitivity results because they show the effect only on the mean annual recharge for the basin as a whole. Recharge for certain landscapes may be more or less sensitive than indicated by the results in figure10A. For example, the sensitivity of simulated recharge to the maximum depth of evapotranspiration is greater for a landscape unit where the maximum depth of evapotranspiration is small compared to the total soil thickness than for a landscape unit where that maximum depth of evapotranspiration is large compared to the total soil thickness.

Sensitivity of the mean annual recharge, surface runoff, and evapotranspiration to changes in selected input parameters for a single landscape unit was simulated by using the water-budget model (fig. 11). The analysis was conducted to illustrate how changes in model parameters over the range of values used in the model for the different landscape units could affect the simulated average water budget for 1951-2000. The landscape unit with Berks-Weikert soil and land-use/land-cover designation of “crop” was chosen for the analysis because it is the most widely distributed soil-type/land-cover combination, comprising about 32 percent of the watershed. The sensitivity analysis for the single landscape unit shows how differently the parameters affect the simulated water-budget terms over the full range of plausible values for those parameters. Note how changes in some parameters cause a fairly linear change in simulated recharge, surface runoff, and evapotranspiration throughout the range of values tested (for example, specific yield, hydraulic conductivity, and precipitation in figure 11). Alternately, changes in other parameters cause a nonlinear change in simulated water-budget terms (for example, available water-holding capacity, runoff-curve number, layer thickness, and maximum depth of evapotranspiration in figure 11). A nonlinear response means that the sensitivity of the model to a change in a parameter depends on the value of the parameter. For example, a change of runoff-curve number (CN) from 60 to 65 has no effect on simulated recharge, surface runoff, or evapotranspiration; whereas, a change from 90 to 95 has a large effect on all three water-budget terms.

Comparison to Other Recharge Estimates

Simulated recharge from the water-budget model was compared to recharge and base-flow estimates obtained from streamflow-hydrograph analysis using the computer programs RORA and PART (Rutledge, 1998). The RORA program uses the recession-curve displacement technique of Rorabaugh (1964) to estimate ground-water recharge from each storm period on the hydrograph. The RORA program is not a hydrograph-separation method; rather, recharge is determined from displacement of the streamflow-recession curve for each storm according to the theory of ground-water drainage. The PART computer program uses a hydrograph-separation technique to delineate the base-flow component of the streamflow record. Base flow is the part of streamflow not attributable to surface runoff from precipitation or snowmelt. Although base flow is not recharge, it has been used as an approximation of recharge when the investigator believes that base flow represents ground-water discharge and that ground-water discharge is approximately equal to recharge. Because a substantial quantity of underflow is not measured at the streamflow-gaging station on Jordan Creek at Allentown (Wood and others, 1972), recharge and base-flow estimates based on streamflow records from the gaging station near Schnecksville (where underflow is not substantial) were used.

During 1967-2000, on the basis of the streamflow hydrograph at Schnecksville, mean annual recharge computed by the RORA method averaged 19.3 in/yr, and base flow computed from PART averaged 15.1 in/yr (Risser and others, 2005b). Mean annual recharge from the water-budget method for the part of the Jordan Creek watershed upstream from the streamflow-gaging station at Schnecksville for 1967-2000 was 12.4 in. Although recharge estimated from the water-budget method is smaller than estimates derived from the streamflow records, all estimates are reasonable.

Comparison to Streamflow Measurements

Even though the estimated mean annual recharge of 12.4 in. from the water-budget method is reasonable, the small quantity of surface runoff simulated by the model suggests that the water-budget results are suspect. The volumes of surface runoff and recharge simulated by the water-budget model should, when summed, approximately equal the streamflow measured at the gaging station near Schnecksville, because the recharge should return to the stream as base flow. Mean annual surface runoff simulated by the water-budget method during 1967-2000 was about 4.5 in/yr, which, when added to the estimate of recharge of 12.4 in/yr, gives 16.9 in/yr of simu-

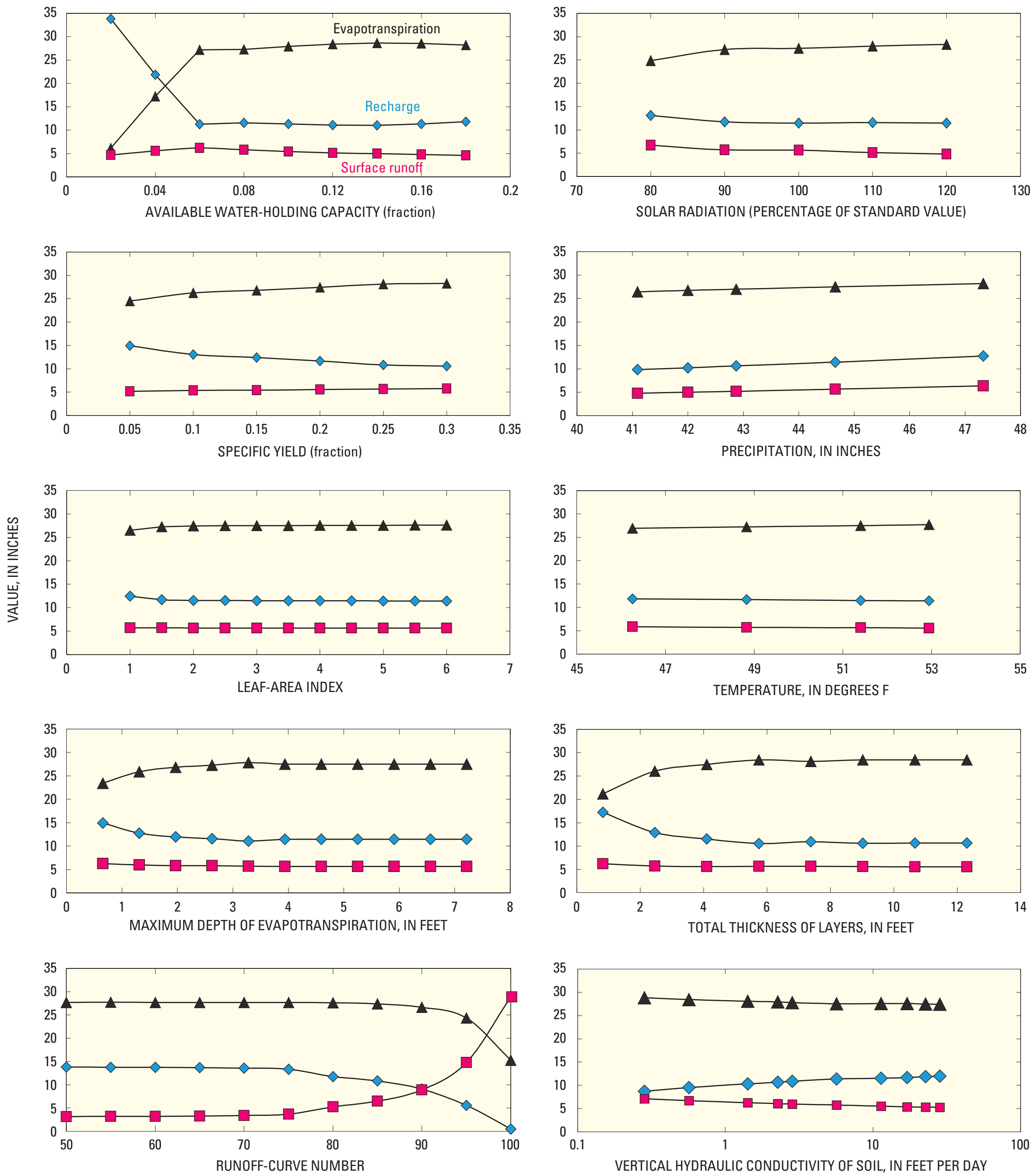


Figure 11. Sensitivity of mean annual recharge, surface runoff, and evapotranspiration simulated by the water-budget model to changes in selected input parameters for a single landscape unit during 1951-2000 within the Jordan Creek watershed, Lehigh County, Pa.

lated streamflow. During 1967-2000, mean annual streamflow at Schnecksville was 23.9 in/yr. The simulated value is 7 in/yr less than the 23.9 in/yr of streamflow measured at the gaging station during that period, indicating that evapotranspiration (28.2 in/yr) simulated by the water-budget model may be overestimated by about 7 in/yr.

The reason that HELP apparently overestimates evapotranspiration and underestimates surface runoff in the study area is not clear. Several input parameters affect the computation of evapotranspiration, so errors in estimating the parameters could be partly responsible. For the Jordan Creek watershed, sensitivity of simulated evapotranspiration to selected input variables was computed (fig. 10B). For the study area, increases in runoff-curve number and wilting point cause a decrease in the simulated evapotranspiration, whereas a decrease in precipitation, temperature, and solar radiation have the greatest effect on decreasing evapotranspiration. However, it would take a large change in input parameters to affect a decrease in evapotranspiration of 7 in/yr. Figure 11 shows that a reduction in simulated evapotranspiration of 7 in/yr (to about 21 in/yr) in a Berks-Weikert soil could be achieved only at small values of available water-holding capacity and soil-layer thickness or large values of runoff-curve number; however, these values are extremes that would not be considered reasonable values for most of the landscape units within the watershed.

Although inaccurate estimates of input parameters could be responsible, Berger (2000) pointed out errors in the computation of evapotranspiration in the HELP model, and Hauser and others (2005) found that the HELP model did not accurately estimate evapotranspiration at a site in Ohio. Thus, the apparent overestimate of evapotranspiration at the Jordan Creek watershed could be caused by limitations in the model algorithms that would not be remedied by better estimates of input data. Although the HELP model was chosen for this study, other water-budget models, such as **E**rosion **P**roductivity **I**mpact **C**alculator (EPIC) (Mitchell and others, 1998) or the deep percolation model of Bauer and Vaccaro (1987), are available. Hauser and others (2005) found that EPIC gave better estimates of water-budget terms when compared to the HELP model at sites where the models were compared in Ohio and Texas.

Summary and Conclusions

This study, conducted by the U.S. Geological Survey in cooperation with the Pennsylvania Department of Conservation and Natural Resources, Bureau of Topographic and Geologic Survey, illustrates a method for mapping the spatial distribution of ground-water recharge at a sub-watershed scale. The method involved computing recharge by using a water-budget model and mapping the distribution of mean annual recharge by use of a geographic information system (GIS). The method, which could have applicability for land-use planning and water-management projects, was applied in the 76-mi^2 part of the Jordan Creek watershed upstream from the streamflow-gaging station at Allentown, Pa.

The water-budget model Hydrological Evaluation of Landfill Performance (HELP) version 3.07 was used in the Jordan Creek watershed to estimate mean annual recharge for 577 landscape units having differing physical properties and using climate data for the period 1951-2000. The landscape units in the study area were identified from GIS data layers of soils, land use/land cover, and mean annual precipitation. The quantity of percolation leaving the bottom of layer 5 in the water-budget model was assumed to be ground-water recharge. It is possible that some water in the unsaturated zone below the base of layer 5 does not reach the water table, and instead it could move laterally as interflow to a discharge point; thus, percolation simulated by the water-budget model represents an estimate of the potential amount of recharge that could reach the water table.

Precipitation, evapotranspiration, surface runoff, recharge, and change in storage were simulated by the water-budget model on a daily basis from 1951 to 2000 for each of 577 landscape units and were summarized by month and year. Simulated mean annual recharge for the period 1951-2000 was 12.3 in/yr, ranging from 0.11 in/yr for a wetland landscape to 17.1 in/yr for an upland soil. Mean annual recharge for 73 percent of the landscape units ranged from 9 to 14 in/yr.

The crop, forest, pasture, and low-density urban land-use/land-cover classes had similar annual recharge rates (11.2 to 12.2 in/yr) but were greater than other land-use/land-cover classes such as high-density residential (6.8 in/yr), herbaceous wetlands (2.5 in/yr), and forested wetlands (1.3 in/yr). Estimates of mean annual recharge for the crop, forest, pasture, and low-density urban land-use/land-cover classes are similar because these classes are on the same types of soil and receive the same range of precipitation. The differing land-use/land-cover classes mostly affect the model input parameters of leaf-area index, runoff-curve number, and maximum depth of evapotranspiration. Recharge simulated by the water-budget model is not sensitive to leaf-area index, and values of runoff-curve number and maximum depth of evapotranspiration tended to be offsetting. The smaller simulated mean annual recharge rates for high-density urban (6.8 in/yr) and wetland land-use/land-cover classes (2.5 and 1.3 in/yr) were caused by the large values of runoff-curve numbers (greater than 90) assigned to those classes.

The small simulated values of recharge for wetlands were predetermined by the large runoff-curve number of 98 specified for wetlands, causing nearly all water to run off. There was no guidance in SCS Technical Release 55 for estimating the runoff-curve number for wetlands, so a judgment was made that runoff from wetlands would be a large percentage of precipitation. This certainly is not realistic for all wetlands; some wetlands act as areas of ground-water discharge and some as areas of recharge. Choosing reasonable model parameters to characterize wetlands is a problem with using the water-budget approach.

The value of mean annual recharge during 1951-2000 simulated by the water-budget model was most sensitive to changes to input values for precipitation and runoff-curve number. A 10-percent increase in precipitation caused a 19-percent increase in recharge; a 10-percent increase in runoff-curve number caused a 15-percent decrease in recharge. Simulated recharge was sensitive to values of temperature, porosity, and wilting point. Some caution, however, is needed in interpreting the sensitivity results, because the sensitivity analysis shows the effect only on the mean annual recharge for the basin as a whole. Recharge for certain landscapes may be more or less sensitive than for the watershed as a whole. Sensitivity analysis for a single landscape unit showed how changes in some parameters cause a fairly linear change in simulated recharge and changes in other parameters cause a nonlinear change that depends on the value of the parameter. For example, a change of runoff-curve number (CN) from 60 to 65 has no effect on simulated recharge, whereas a change from 90 to 95 has a large effect.

The sensitivity analysis showed the importance of accurate data to characterize model input parameters. Most of the model parameters were derived from available climate, soils, and land-use/land-cover datasets, but in many cases, the parameters were not directly available from the datasets. Usually the quantitative model parameters (for example wilting point, maximum depth of evapotranspiration, and leaf-area index) were derived indirectly from the land-use/land-cover and soils datasets. Even the climate data required manipulation to estimate missing record and extrapolate values from available stations.

Simulated mean annual recharge from the water-budget model during 1967-2000 of 12.4 in. was less than estimates of recharge (19.3 in.) and base flow (15.1 in.) from hydrograph analysis of streamflow measured at the USGS streamflow-gaging station near Schnecksville, but the estimate from the water-budget model is certainly reasonable. However, comparisons of streamflow measured at the gaging station to that simulated by the model indicate that evapotranspiration is probably overestimated by the water-budget model by about 7 in/yr, which probably causes surface runoff and recharge to be underestimated. Incorrect estimates of input parameters could be responsible for the apparent overestimate of evapotranspiration as could some limitations in the HELP model algorithms. Given this uncertainty, determinations of the spatial variability of recharge within Jordan Creek watershed may not be reliable.

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Risser— **Spatial Distribution of Ground-Water Recharge Estimated with a Water-Budget Method**—Scientific Investigations Report 2008-5041

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