Documentation of the Highlands Regional Rainfall-Runoff Model, Southeastern and South-Central Pennsylvania

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Introduction

The Highlands Conservation Act, signed by President George W. Bush on Nov. 30, 2004, is designed to assist Connecticut, New York, New Jersey, and Pennsylvania conserve land and natural resources in the Highlands Region through federal assistance for land-conservation projects in which a state entity acquires land or an interest in land from a willing seller to permanently protect resources of high conservation value (United States, PL 108-421, 2004). The purposes of the Highlands Conservation Act are to recognize the importance of the water, forest, agricultural, wildlife, recreational, and cultural resources of the Highlands Region and the national significance of the Highlands Region to the United States (United States, PL 108-421, 2004).

A resource assessment of the Pennsylvania Highlands Region was needed to evaluate the likely effects of future urban growth on the resources of the region, including water resources. An important issue in the Highlands is protection of surface-water and ground-water quality and quantity (United States, PL 108-421, 2004). One major task of the Highlands Regional study was to create a hydrology simulation model to analyze the effect of build-out scenarios on water resources.

The U.S. Geological Survey (USGS) Pennsylvania Water Science Center (PaWSC) partnered with the Yale School of Forestry & Environmental Studies, Global Institute of Sustainable Forestry; the State University of New York (SUNY), College of Environmental Science and Forestry; the Regional Planning Association (RPA); and the Appalachian Mountain Club (AMC) to conduct the Pennsylvania Highlands Regional Study for the U.S. Forest Service. The PaWSC was tasked with evaluating the water resources of the Pennsylvania Highlands, which included constructing a rainfall-runoff model.

The quantity, quality, and distribution of water recharging an aquifer or running overland to streams can be affected by the land uses with which the water interacts. An increase in impervious surfaces such as parking lots, buildings, and roads decreases the amount of pervious land surface through which precipitation can infiltrate, thus reducing water availability to soils and recharge to ground-water supplies. At the same time as less precipitation infiltrates the land surface, the amount of runoff increases; this increases the potential for soil erosion, flooding, and surface-water contamination. This decreased infiltration also changes the distribution of streamflow. During dry periods, less water flows as stream base flow, and during wet periods, more water flows as immediate runoff. These changes in the hydrology of a watershed commonly are accompanied by a range of hydrological and ecological impacts: increased frequency of flooding for similar storm events, decreased water-supply storage during droughts, degraded water quality, and stressed ecosystems. A water budget under current land-use conditions compared to an estimated water budget under altered land-use conditions would offer insight into the effects of those land-use alterations on the water budgets.

A rainfall-runoff hydrologic model of the Highlands was constructed to estimate water-budget information at a 14-digit hydrologic unit code (HUC 14) subwatershed scale. The model also was used to evaluate changes in the water budget under projected conditions of increased development. Projected conditions were simulated through a build-out analysis conducted by the RPA. RPA evaluated maximum potential residential growth on the basis of current municipal zoning regulations with and without additional constraints. The analysis provided information about potential increases in development and impervious area for the Pennsylvania Highlands Region. Results of the build-out analysis were incorporated into the hydrologic model to determine the effects these build-out scenarios might have on water resources of the Pennsylvania Highlands.

Purpose and Scope

This report describes the data sources, construction, and calibration of a rainfall-runoff model used for the assessment of existing and potential changes to the water resources of the Highlands of Connecticut and Pennsylvania (U.S. Forest Service, 2006). Included in this report are modeling results of water budgets at HUC 14 subwatershed scales and results of land-use changes, specifically increased impervious cover, on water budgets of the Pennsylvania Highlands Region.

Rainfall-Runoff Model

A hydrologic model of the Highlands was constructed to estimate water-budget information for watersheds in the region. Unlike a regional water budget, watershed-scale budgets provide a better accounting of local variability in hydrologic conditions among individual watersheds. The model also was used to evaluate changes in the water budget given projected future conditions such as increased development. The Pennsylvania Highlands model simulates the hydrologic cycle using detailed climatic, topographic, geologic, land-cover, and soils data and from that derives individual components of the water budget. In this way, water-budget information can be obtained using a model where measured data are lacking. The USGS Precipitation-Runoff Modeling System (PRMS) (Leavesley and others, 1983) was selected to simulate the complex interaction of climatic, topographic, geologic, land-cover, and soils data of the Highlands Region.

Description of Precipitation-Runoff Modeling System (PRMS)

PRMS is a modular, physically based, distributed-parameter modeling system developed to evaluate the impacts of various combinations of precipitation, climate, and land use on surface-water runoff and general basin hydrology (Leavesley and others, 1983). PRMS is physically based in that each component of the hydrologic system is simulated with known physical laws or empirical relations formulated on the basis of measurable watershed characteristics (Yeung, 2005). PRMS models a watershed as an interconnected series of reservoirs, including interception storage in the vegetation canopy and storages in the soil zone, subsurface reservoir, and ground-water reservoir (fig. 1). Flows into and out of the PRMS reservoirs represent various processes of the hydrologic cycle. Total system response or streamflow is the sum of surface, subsurface, and ground-water flow. Complete documentation for the modeling system is available in the PRMS user's manual (Leavesley and others, 1983).

PRMS architecture consists of various user-selected modules that represent the different components of the hydrologic system and that simulate the processes associated with them (table 1).

The distributed-parameter and watershed-partitioning features of the PRMS are designed to account for the spatial variation in watershed characteristics. A watershed is partitioned into small units within which the slope, land use, soil, geology, and precipitation distribution are similar (Yeung, 2005). Within each unit, the hydrologic response is assumed to be homogeneous, thus each unit is referred to as a hydrologic response unit (HRU). Heterogeneity within an individual HRU is accounted for by computing areally weighted averages for each characteristic (Yeung, 2005). A daily water balance and energy balance are computed for each HRU, and the daily total watershed response is the areally weighted sum of the responses of all the HRUs (Yeung, 2005).

Building the Model

The modeled area for the Pennsylvania Highlands totals 3,050 mi^2 (square miles) in an area roughly bounded by the Delaware River on the east and the Susquehanna River on the west (fig. 2). The area includes the headwaters portion of eight major streams, the lower reaches of four major streams, and the entire watersheds of numerous small streams that drain directly to the Delaware or Susquehanna Rivers. The modeled area is 42 percent larger than the 2,150 mi^2 within the Highlands proper because the model boundary is demarcated by hydrologic considerations rather than the primarily political boundary of the Highlands. These considerations require that the model boundary falls on natural watershed boundaries and conforms to the choice of scale for defining individual watersheds. The watershed scale used in the model is defined

Table 1. List of Precipitation-Runoff Modeling System (PRMS) modules used in the Pennsylvania Highlands model.

[HRU, hydrologic response unit]

PRMS model module	Description
SOLTAB_HRU	Computes potential solar radiation
XYZ_DIST	Distributes precipitation and temperatures to each HRU
DDSOLRAD_HRU	Distributes solar radiation to each HRU, also estimates missing data
POTET_JH	Computes and distributes potential evapotranspiration to each HRU
INTCP	Computes interception and evaporation of intercepted rain and snow; also net rain and snow to each HRU
SNOWCOMP	Simulates snow accumulation and depletion processes for each HRU
SRUNOFF_SMIDX	Computes surface runoff and infiltration for each HRU
SMBAL	Soil moisture accounting for each HRU
SSFLOW	Adds inflow to subsurface reservoirs and computes outflow to ground-water reservoirs and streamflow
GWFLOW	Sums inflow to ground-water reservoirs and computes outflow to streamflow
STRMFLOW_SUBBASIN	Computes daily streamflow at basin outlet and internal subbasins

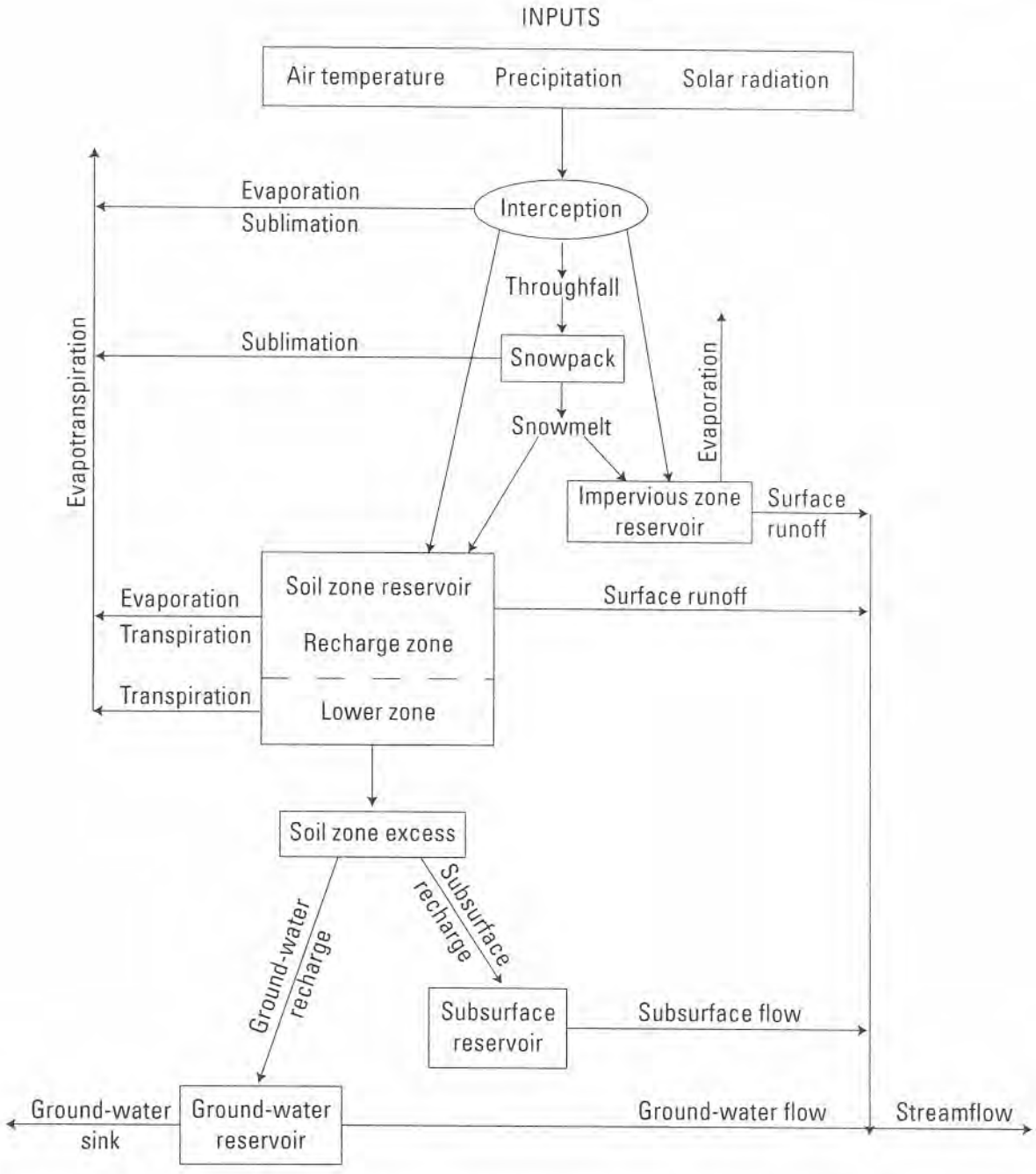

Figure 1. Conceptual hydrologic system of the Precipitation-Runoff Modeling System (from Ely and Risley, 2001).

Table 2. HUC 14 subwatersheds contributing to the Pennsylvania Highlands. (Map identifier cross references subwatersheds to figure 3 map.)

Map identifier	14-digit hydrologic unit code	Local stream name	Drainage area (square miles)	Drainage area within Highlands (square miles)
1	02040105105240	Bushkill	62.5	21.0
2	02040105110040	Mud Run	13.1	5.8
3	02040105120020	Delaware River Tributaries	4.9	4.8
4	02040105140070	Frya Run	7.7	7.7
5	02040105170005	Tinicum and Cooks Creeks	29.5	29.5
6	02040105170055	Tinicum and Cooks Creeks	24.0	24.0
7	02040105170070	Tinicum and Cooks Creeks	30.9	30.6
8	02040105180220	Tohickon Creek	34.5	34.5
9	02040105180240	Tohickon Creek	48.3	48.3
10	02040105180260	Tohickon Creek	29.4	28.7
11	02040105210020	Paunnacussing Creek	19.9	3.9
12	02040106060240	Jordan Creek	33.2	3.2
13	02040106070240	Little Lehigh Creek	42.1	39.7
14	02040106070260	Little Lehigh Creek	41.7	33.0
15	02040106080400	Lower Lehigh River	33.5	11.4
16	02040106080420	Lower Lehigh River	57.9	57.9
17	02040106080440	Lower Lehigh River	6.1	6.1
18	02040106080460	Lower Lehigh River	40.7	31.7
19	02040201105220	North Branch Neshaminy Creek	31.7	11.9
20	02040203030280	Maiden Creek	23.0	7.0
21	02040203030300	Maiden Creek	32.3	27.4
22	02040203030320	Maiden Creek	21.7	21.7
23	02040203030340	Maiden Creek	37.9	30.6
24	02040203040220	Tulpehocken Creek	38.5	11.1
25	02040203040240	Tulpehocken Creek	16.1	14.4
26	02040203040260	Tulpehocken Creek	34.4	6.1
27	02040203040320	Tulpehocken Creek	31.1	19.2
28	02040203040360	Tulpehocken Creek	21.8	14.2
29	02040203040380	Tulpehocken Creek	19.2	2.1
30	02040203050260	Middle Schuylkill River	39.8	3.2
31	02040203050280	Middle Schuylkill River	25.0	20.5
32	02040203050300	Middle Schuylkill River	15.7	12.8
33	02040203050320	Middle Schuylkill River	17.9	17.9
34	02040203050340	Middle Schuylkill River	17.6	17.6
35	02040203050360	Middle Schuylkill River	40.2	38.8
36	02040203050380	Middle Schuylkill River	22.1	22.1
37	02040203050400	Middle Schuylkill River	25.8	25.8
38	02040203050420	Middle Schuylkill River	30.4	30.4
39	02040203060220	Manatawny Creek	23.6	23.6
40	02040203060240	Manatawny Creek	15.5	15.5
41	02040203060260	Manatawny Creek	52.5	52.5
42	02040203070220	French Creek	23.2	23.2
43	02040203070240	French Creek	46.9	39.5
44	02040203080220	Perkiomen Creek	18.0	18.0
45	02040203080240	Perkiomen Creek	23.8	23.8
46	02040203080260	Perkiomen Creek	17.4	17.4
47	02040203080280	Perkiomen Creek	48.8	48.8
48	02040203080300	Perkiomen Creek	43.6	43.6
49	02040203080320	Perkiomen Creek	55.5	55.5

Table 2. HUC 14 subwatersheds contributing to the Pennsylvania Highlands. (Map identifier cross references subwatersheds to figure 3 map.)

Map identifier	14-digit hydrologic unit code	Local stream name	Drainage area (square miles)	Drainage area within Highlands (square miles)
50	02040203080340	Perkiomen Creek	61.0	41.8
51	02040203080360	Perkiomen Creek	55.8	21.6
52	02040203080380	Perkiomen Creek	38.3	21.2
53	02040203100220	Lower Schuylkill River	14.5	14.5
54	02040203100240	Lower Schuylkill River	32.6	32.6
55	02040203100260	Lower Schuylkill River	38.8	7.9
56	02040203100300	Lower Schuylkill River	51.8	9.4
57	02040205010220	East Branch Brandywine Creek	20.3	20.2
58	02040205010240	East Branch Brandywine Creek	43.5	29.6
59	02040205010260	East Branch Brandywine Creek	18.0	3.3
60	02040205020240	West Branch Brandywine Creek	58.2	42.1
61	02040205020280	West Branch Brandywine Creek	26.9	9.1
62	02050305050300	Yellow Breeches Creek	44.4	14.2
63	02050305080220	Quittapahilla Creek	15.0	10.0
64	02050305080240	Quittapahilla Creek	62.3	33.3
65	02050305090280	Swatara Creek	24.0	21.0
66	02050305090320	Swatara Creek	37.3	20.0
67	02050305100360	East Conewago Creek	17.8	17.8
68	02050305100380	East Conewago Creek	52.5	52.5
69	02050305100400	East Conewago Creek	46.1	19.9
70	02050306050280	West Conewago Creek	5.7	2.7
71	02050306050300	West Conewago Creek	36.2	23.2
72	02050306080220	Chiques Creek	49.2	46.2
73	02050306080240	Chiques Creek	44.5	40.8
74	02050306080260	Chiques Creek	17.2	6.6
75	02050306080280	Chiques Creek	15.1	4.5
76	02050306090220	Cocalico Creek	47.8	47.8
77	02050306090240	Cocalico Creek	12.0	12.0
78	02050306090260	Cocalico Creek	32.3	32.3
79	02050306090280	Cocalico Creek	35.3	31.3
80	02050306090300	Cocalico Creek	12.7	6.7
81	02050306100220	Little Conestoga Creek	36.6	4.4
82	02050306110220	Conestoga River	61.2	61.2
83	02050306110240	Conestoga River	16.1	16.1
84	02050306110260	Conestoga River	35.7	35.7
85	02050306110280	Conestoga River	27.3	8.1
86	02050306110300	Conestoga River	17.4	4.3
87	02050306110320	Conestoga River	56.4	14.7
88	02050306120220	Pequea Creek	65.6	58.1
89	02050306120240	Pequea Creek	34.0	24.1
90	02050306120260	Pequea Creek	21.4	8.8
91	02050306160220	Susquehanna River Tributaries	19.0	18.7
92	02050306160240	Susquehanna River Tributaries	37.7	12.2
93	02050306180220	East Branch Octoraro Creek	18.1	18.1
94	02050306180240	East Branch Octoraro Creek	20.4	13.5
95	02050306220220	West Branch Octoraro Creek	48.1	19.9

by HUC 14 units, which are formally called subwatershed units (Seaber and others, 1984). The HUC 14 subwatershed scale was selected to maintain consistency with a hydrologic analysis completed for the New York and New Jersey Highlands Region (U.S. Department of Agriculture Forest Service, 2002). A HUC series (from 2-digit through 14-digit) establishes the nominal size of the area bounded by the HUC. In the Pennsylvania Highlands, HUC 14 subwatersheds have an average area of about 32 mi^2 and a maximum area of 66 mi^2. The Pennsylvania Highlands area contains all or parts of 95 HUC 14 subwatersheds (fig. 3 and table 2).

The objective of the modeling effort was to estimate annual water budgets for the HUC 14 subwatersheds under existing conditions and under projected conditions assuming additional development (build-out) within the Highlands. Given this objective, the model was developed using a daily time step and no channel routing of streamflow.

Hydrologic Response Units (HRUs)

A PRMS model is designed around the concept of partitioning a watershed into units on the basis of characteristics such as slope, aspect, vegetation type, soil type, and precipitation distribution. Each unit is considered homogeneous with respect to its hydrologic response and is called a HRU (Leavesley and others, 1983). Output from PRMS is also partitioned by HRU. Because of the desire to obtain water-budget information for each HUC 14 subwatershed, the model HRUs were delineated by the HUC 14 subwatershed boundaries. To ensure the HUC 14 subwatersheds satisfied the concept of an HRU, the homogeneity of characteristics such as slope, vegetation type, geology, and soil type of the HUC 14 was reviewed. Additionally, 25 HUC 14 subwatersheds were subdivided at locations of USGS streamflow-gaging stations to permit model output at and calibration for these locations. With the added subdivisions, a total of 133 HRUs were generated for the model (fig. 4). Individual output for HRUs within the subdivided HUC 14 subwatersheds was aggregated to the parent HUC 14 subwatersheds for presentation of results.

Model Input Data

Input data consist of times-series data and physical-characteristic data. Time-series data are structured on a daily time step and are used either as input to (climate data) or for calibration (streamflow data) of the model. Time-series data were acquired to cover at a minimum the simulation period (1986–2001) plus an additional year to allow for initialization. The simulation period was chosen to achieve a balance between selecting a period sufficiently long to include a range of climatic conditions and selecting one specific enough to represent "existing" land-cover conditions as portrayed in the 2001 National Land Cover Data (NLCD 2001) (Multi-Resolution Land Characteristics Consortium, 2007). The physical-characteristic data typically are expressed as constants to be used in the parameterization process. These data were determined from GIS analysis of spatial data sets of the model basin, from published methods, or from model default values.

Climate Data

Climate data for the model consisted of precipitation, minimum and maximum air temperature, and solar radiation. Daily data from 43 National Weather Service Cooperative Climate Stations in the vicinity of the Pennsylvania Highlands were parsed for precipitation and minimum and maximum air temperature data. Data from a subset of these stations were distributed to the individual HRUs using a multiple linear-regression-relation method (XYZ) developed for each month using the values of the climate variables and the x, y, and z coordinates of the stations (Hay and others, 2000, 2002). The final best-fit XYZ model used 19 of the 43 stations (fig. 4 and table 3). The XYZ output consisted of daily values of precipitation and minimum and maximum air temperature adjusted for monthly climatic trends correlated with the location and elevation of each HRU. Daily solar-radiation data from the National Solar Radiation Database (NSRDB) (U.S. Department of Energy, National Renewable Energy Laboratory, 2007) were acquired for two stations—Capital City Airport (WBAN# 14751) situated near the western end of the Highlands and Allentown-Bethlehem-Easton Airport (WBAN# 14737) near the eastern end (fig. 4). Distribution of solar-radiation data was accomplished by mapping each HRU to the closest solar-radiation station.

Streamflow Data

Daily streamflow data from 14 USGS streamflow-gaging stations (table 4 and fig. 5) were acquired for use in model calibration. The streamflow data represent areas draining from 8.6 to 324 mi^2. In total, these data account for streamflow from 37 percent of the modeled area and 41 percent of the Pennsylvania Highlands area.

Physical-Characteristic Data

Physical-characteristic data consisted of spatial data sets describing topography, geology, soils, land cover, and forest cover. Topographic characteristics were derived from the 1-arc second National Elevation Dataset (U.S. Geological Survey, 1999). Generalized geology was derived from Berg and others (1980). Soils data and forest type were acquired from the GIS Weasel Data Bin (Viger and Leavesley, 2007). Imperviousness, land cover, and forest density (canopy cover) data sets were obtained from the NLCD 2001 database (Multi-Resolution Land Characteristics Consortium, 2007).

Model Parameterization

Within PRMS, basic hydrologic processes of an HRU are tailored to the hydrologic characteristics of the watershed through the parameterization process. Parameters in PRMS

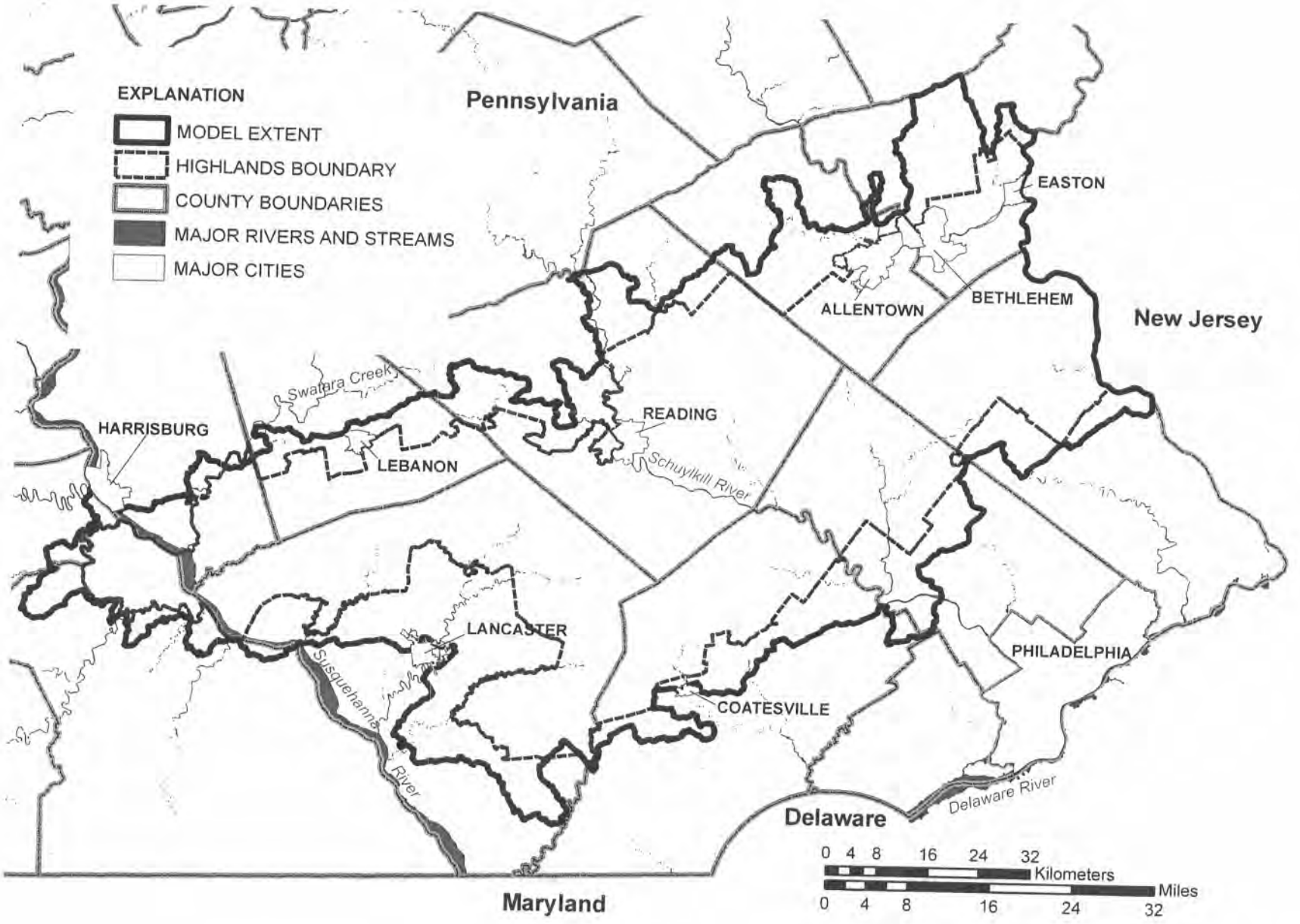

Figure 2. Location of the Pennsylvania Highlands and extent of the Highlands model.

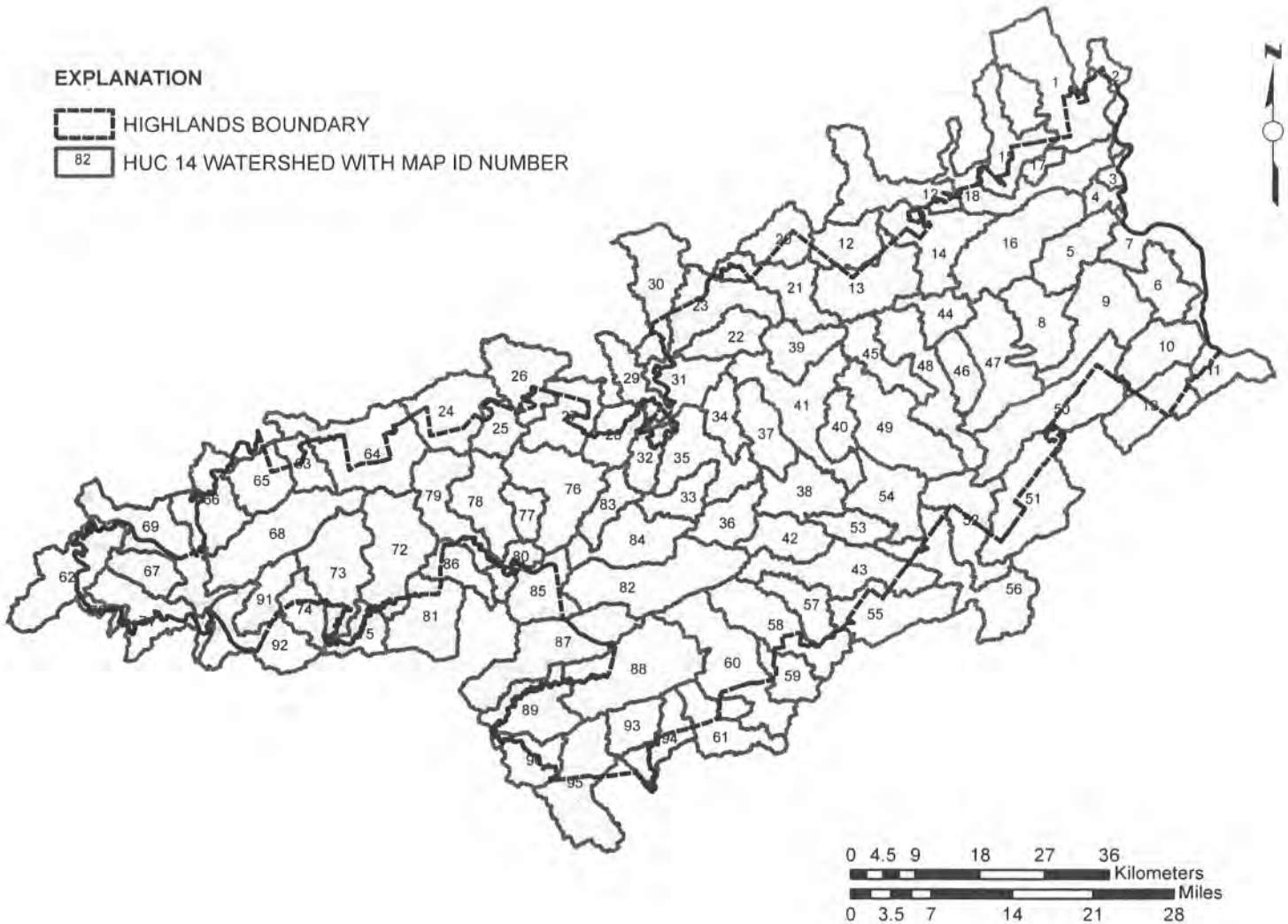

Figure 3. HUC 14 subwatersheds contributing to the Pennsylvania Highlands. Map ID numbers cross reference to table 2 and appendix 1.

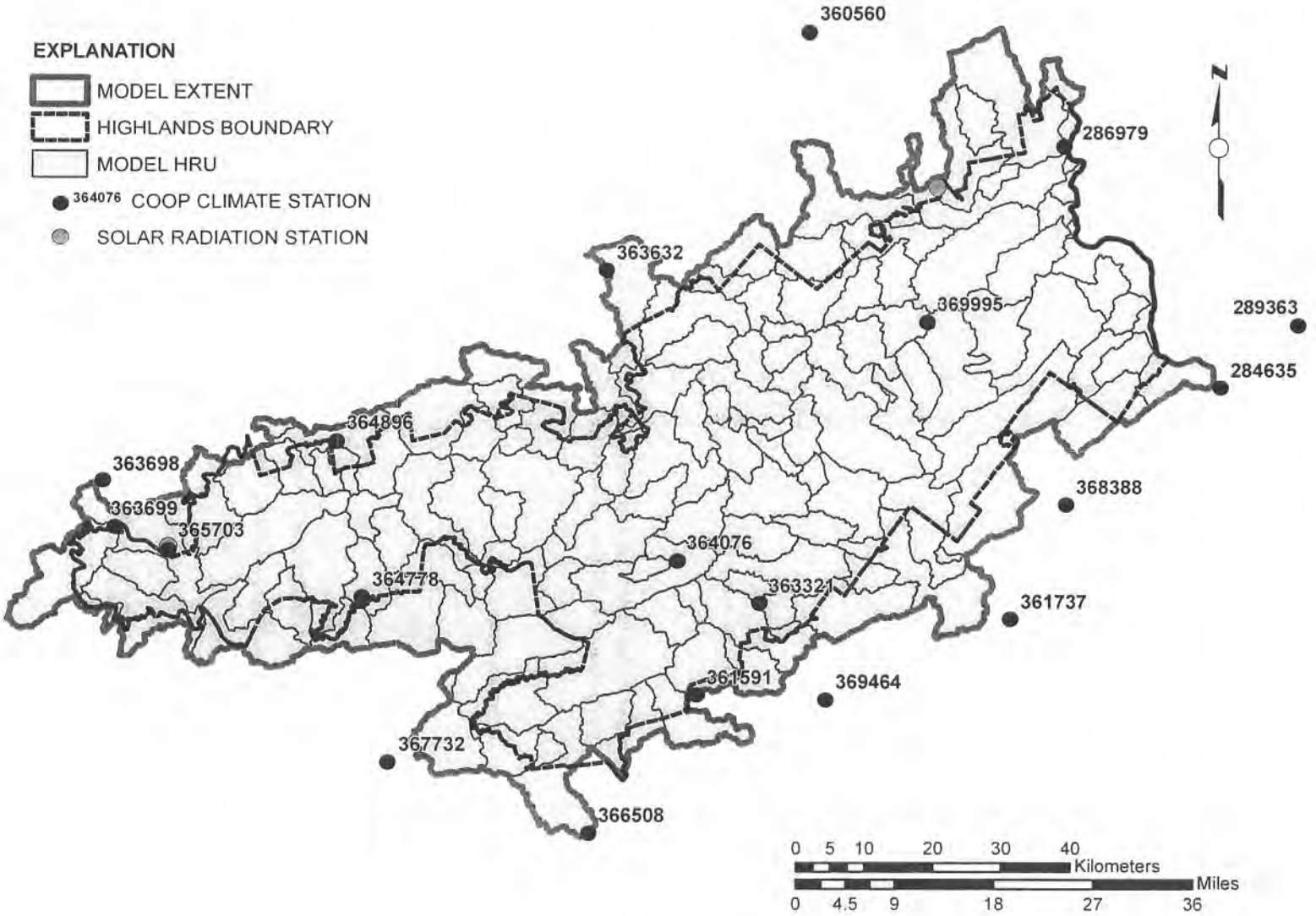

Figure 4. Hydrologic response units (HRU), climate stations, and solar-radiation stations used in the Pennsylvania Highlands model.

Table 3. Cooperative climate stations used in the Pennsylvania Highlands Precipitation-Runoff Modeling System (PRMS) model. (Locations of climate stations are shown on figure 4.)

Station identifier	Station name	Latitude	Longitude	Elevation (feet above sea level)
284635	Lambertville	40.37	-74.95	68
286979	Phillipsburg-Easton Bridge	40.70	-75.20	200
289363	Wertsville 4 NE	40.45	-74.81	240
360560	Beltzville Dam	40.86	-75.64	735
361591	Coatesville 2 W	39.98	-75.86	640
361737	Conshohocken	40.07	-75.32	70
363321	Glenmoore	40.10	-75.75	500
363632	Hamburg	40.55	-76.00	350
363698	Harrisburg 1 NE	40.28	-76.87	420
363699	Harrisburg Capital City AP	40.22	-76.85	340
364076	Hopewell	40.16	-75.89	550
364778	Landisville 2 NW	40.12	-76.43	360
364896	Lebanon 2 W	40.33	-76.47	450
365703	Middletown-Harrisburg International AP	40.19	-76.76	312
366508	Octoraro Lake	39.80	-76.05	260
367732	Safe Harbor Dam	39.90	-76.39	195
368388	Springhouse 2 NE	40.22	-75.22	240
369464	West Chester	39.97	-75.64	375
369995	Zionsville 3 ESE	40.47	-75.45	585

Table 4. Streamflow-gaging stations selected for use in Pennsylvania Highlands Precipitation-Runoff Modeling System (PRMS) model. (Locations of streamflow-gaging stations are shown on figure 5.)

U.S. Geological Survey streamflow gaging-station number	Station name	Drainage area (square miles)	County
01451500	Little Lehigh Creek near Allentown, Pa.	80.8	Lehigh
01459500	Tohickon Creek near Pipersville, Pa.	97.4	Bucks
01470779	Tulpehocken Creek near Bernville, Pa.	66.5	Berks
01471980	Manatawny Creek near Pottstown, Pa.	85.5	Berks
01472157	French Creek near Phoenixville, Pa.	59.1	Chester
01472198	Perkiomen Creek at East Greenville, Pa.	38	Montgomery
01472199	West Branch Perkiomen Creek at Hillegass, Pa.	23	Montgomery
01473120	Skippack Creek near Collegeville, Pa.	53.7	Montgomery
01480300	West Branch Brandywine Creek near Honey Brook, Pa.	18.7	Chester
01480500	West Branch Brandywine Creek at Coatesville, Pa.	45.8	Chester
01480675	Marsh Creek near Glenmoore, Pa.	8.57	Chester
01573160	Quittapahilla Creek near Bellegrove, Pa.	74.2	Lebanon
01576500	Conestoga River at Lancaster, Pa.	324	Lancaster
01576787	Pequea Creek at Martic Forge, Pa.	148	Lancaster

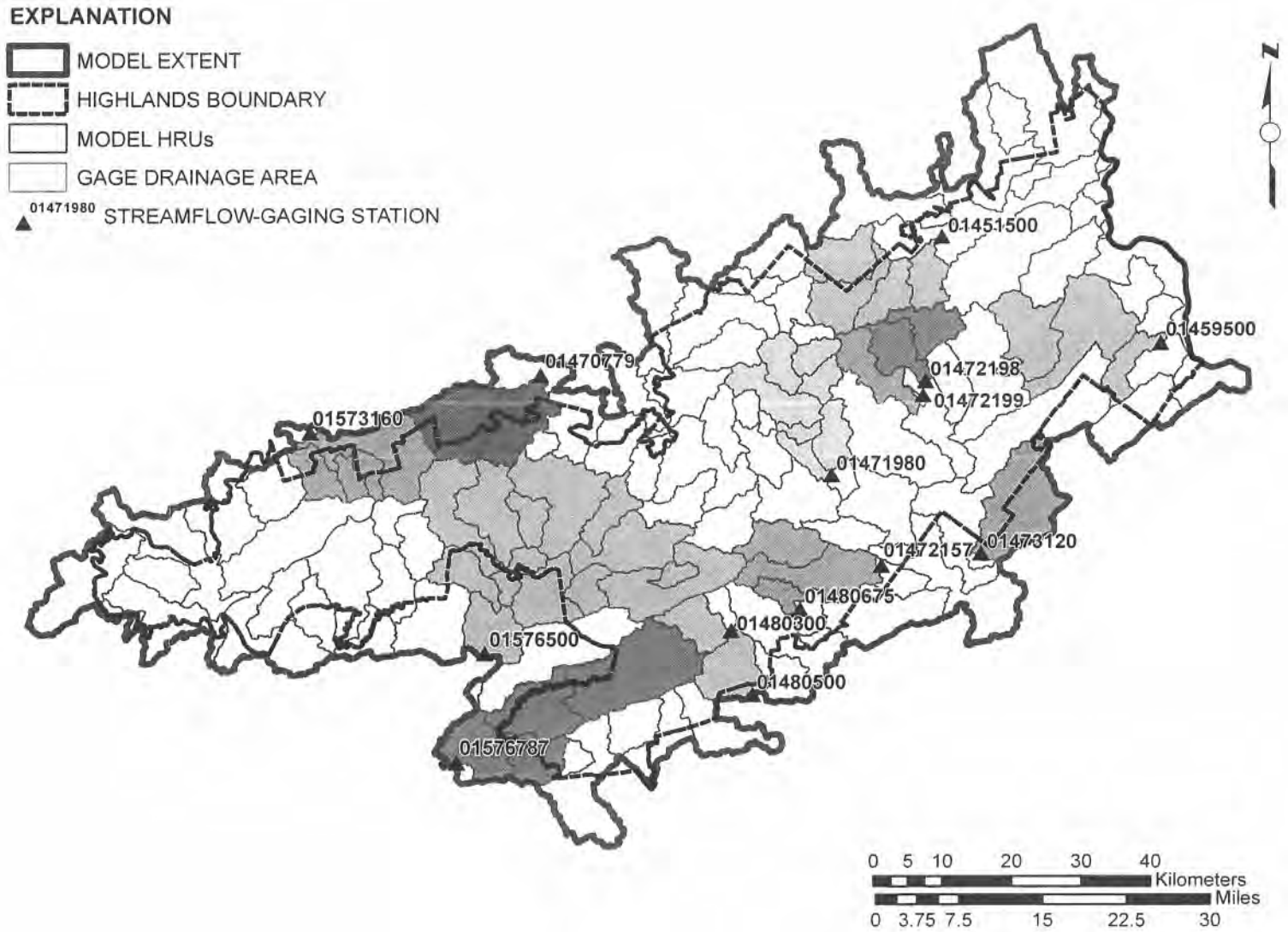

Figure 5. Location and contributing drainage area of 14 streamflow-gaging stations used in the Pennsylvania Highlands model.

are of two general classes: distributed and non-distributed (Yeung, 2005). The distributed parameters typically are derived from spatially variable physical characteristics and are applied to processes on or within an HRU. Non-distributed parameters generally represent characteristics or processes applied to the watershed or model as a whole.

For the Pennsylvania Highlands model, distributed parameters were derived from GIS data sets processed through the GIS Weasel (Viger and Leavesley, 2007). Non-distributed parameters were estimated from regional physical characteristics and local climatic conditions, calculated using algorithms referenced in specific PRMS modules, or assigned default values. In most instances, parameter values were assigned directly from the data and adjusted if necessary during calibration. An important exception to this was impervious area within an HRU. In PRMS, precipitation falling on impervious area is routed directly to streamflow. However, numerous investigators (Alley and Veenhuis, 1983; Laenen, 1983; Sutherland, 2000) have shown that in many instances, runoff from impervious area is routed to pervious surfaces rather than directly to the stream. As a result, the area that functions effectively as impervious can be substantially less than the measured impervious area. For the Pennsylvania Highlands model, an effective impervious area equal to 70 percent of the measured impervious area was chosen to be consistent with that used for the New York and New Jersey Highlands Region (U.S. Department of Agriculture Forest Service, 2002).

Model Calibration

Calibration of the Pennsylvania Highlands model was done on 14 watersheds in the modeled area. These watersheds, covering 1,123 mi^2 out of the 3,050 mi^2 modeled (37 percent), had daily streamflow data suitable for calibration (table 4). The 14 watersheds cover 46 HRUs (fig. 5). The period used for calibration was the same as the simulation period, 1986–2001. Calibration was primarily accomplished using manual methods, but an automated step-wise program named Luca was used to calibrate evapotranspiration (ET) (Hay and Umemoto, 2006).

The initial calibration step was performed on the XYZ precipitation distribution to the HRUs. This step consisted of minimizing an objective function that was defined as the percent difference between precipitation amounts at selected climate stations and the precipitation amounts distributed to the HRUs containing those climate stations. Ten climate stations with the most complete records were selected for calibration. One station had 1.3 percent missing precipitation data; all other stations had less than 1 percent missing data. The parameters adjust_rain and adjust_snow were calibrated using annual and monthly precipitation totals with the objective function. Although a concerted effort was made to minimize errors, both the XYZ regression methodology and spatial averaging across an HRU did not lend themselves to capturing the local variation characteristic of climate-station data. Over an area as large as the Pennsylvania Highlands, this variation was pronounced. Thus, calibration was directed toward distributing the errors uniformly across the modeled area as well as minimizing them. After calibration, the average absolute error for the 10 precipitation stations ranged from 0.2 to -10.4 percent for total annual precipitation and from -1.7 to 4.2 percent for total monthly precipitation. Individual station errors ranged from -21.0 to 47.9 percent for total annual precipitation and from -18.3 to 18.6 percent for total monthly precipitation. The overall mean error for annual totals was 4.7 percent and for monthly totals was 10.6 percent. This positive bias in overall precipitation originates in part in the XYZ method, which applies some amount of precipitation to all HRUs if as few as one climate station reports precipitation, even if that HRU is in a distant part of the basin.

Next, the overall water balance was adjusted through calibration of the ET parameter jh_coef. ET was calibrated for the basin as a whole using the Luca automated step-wise calibration procedure. The objective function used was the absolute differences in the logarithms of the simulated variable basin_actet and estimated ET at the Allentown-Bethlehem-Easton Airport. Daily ET values at the Allentown-Bethlehem-Easton Airport were generated by a modified Penman-Monteith equation (DeGaetano and others, 1994). After calibration, absolute errors in the annual basinwide ET estimates ranged from -26 to 15 percent. The overall average error for the simulation period was -12.8 percent. Examination of the jh_coef parameter after calibration showed only small changes as a result of multiple Luca calibration runs. From the starting default value for jh_coef, calibrated values changed no more than 7 percent of the allowable parameter range. The overall error indicates undersimulation of ET basinwide and, on the basis of water-balance requirements, implies oversimulation of streamflow. Examination of the overall streamflow calibration, however, shows, on average, no bias from the undersimulated ET component.

The average error in annual streamflow for 14 streamflow-gaging stations ranged from -13.1 to 23.4 percent (table 5). The overall mean error (all stations) is 0 percent and suggests the model is not introducing a consistent bias. Pequea Creek at Martic Forge has the greatest average error, a large portion of which is an artifact of the short period of streamflow-gaging station record available for comparison and over-prediction of streamflow by the model during that period. From 1993 to 1995, for which station record is available for Pequea Creek at Martic Forge, model output for all stations with one exception show positive errors ranging from 3.9 to 33.6 percent compared to the average for the simulation period.

Nash-Sutcliffe coefficients (N-S) (Nash and Sutcliff, 1970) also were computed as a general measure of the predictive efficiency of the model (table 5). The N-S coefficient can range from $-\infty$ to 1, with 1 being a perfect match of simulated and observed data. A zero N-S coefficient indicates the simulated values yield accuracy no better than the mean. A negative coefficient implies a biased model. The N-S coefficients for

Table 5. Errors in annual streamflow estimates at streamflow-gaging stations in the Pennsylvania Highlands.

Basin_Name	U.S. Geological Survey streamflow-gaging station number	Percent error in annual estimate of streamflow			Nash_Sutcliffe coefficient	Error analysis period
		Minimum	Maximum	Average		
Little Lehigh Creek near Allentown, Pa.	01451500	2.1	58.5	14.5	0.46	1986–2001
Tohickon Crk nr Pipersville, Pa.	01459500	-.3	-33.2	-.9	.41	1986–2001
Tulpehocken Crk nr Bernville, Pa.	01470779	-1.2	-41.0	-13.1	.42	1986–2001
Manatawny Crk nr Pottstown, Pa.	01471980	-1.6	-44.0	-10.5	.62	1986–2001
French Crk nr Phoenixville, Pa.	01472157	.2	-32.2	-3.2	.53	1986–2001
Perkiomen Crk at E. Greenville, Pa.	01472198	.7	-34.7	-6.5	.51	1986–2001
WBr Perkiomen Crk at Hillegass, Pa.	01472199	0	-39.6	-8.5	.52	1986–2001
Skippack Crk nr Collegeville, Pa.	01473120	2.9	49.6	13.6	.41	1986–1993 (8 years)
WBr Brandywine Crk nr Honey Brook, Pa.	01480300	.5	-36.1	-9.9	.40	1986–2001
WBr Brandywine Crk at Coatesville, Pa.	01480500	-.5	40.0	3.9	.52	1986–2001
Marsh Crk nr Glenmoore, Pa.	01480675	-1.7	28.9	-1.6	.57	1986–2001
Quittapahilla Crk nr Bellegrove, Pa.	01573160	-.6	-33.4	-1.8	.25	1986–1993 (8 years)
Conestoga River at Lancaster, Pa.	01576500	.5	33.0	.7	.60	1986–2001
Pequea Creek at Martic Forge, Pa.	01576787	19.1	29.8	23.4	.43	1993–1995 (32 months)
Average, all basins				0	.48	

the Pennsylvania Highlands model ranged from 0.25 to 0.62 with an overall average value of 0.48.

The partitioning of runoff and base flow was calibrated as the final step. PRMS outputs three flow components: runoff, subsurface flow, and base flow. The subsurface-flow component is generally not reported in water budgets because of its small contribution and lack of measured data for comparison and validation. In most cases, subsurface flow is included in runoff and (or) base-flow estimates. Subsurface flow from the Pennsylvania Highlands model was divided equally between runoff and base flow prior to calibration. The parameters calibrated were smidx_coef and smidx_exp. The values of these parameters were based on functions whose input consisted of an area-weighted value for a generalized ranking of the geology within an HRU. The ranking was derived from the area-weighted average of three general rock types: carbonate (rank 3), crystalline (rank 4), and clastic (rank 5). The HRU ranks ranged from 3.0 (HRU 8) to 5.00 (HRU 34). The weighted ranks were entered into the equations:

$$\text{Smidx_coef} = 0.00000023652 \times e^{(2.5965 \times x)} \quad (1)$$

$$\text{Smidx_exp} = -1.0891 + 1.1766 \times \ln x \quad (2)$$

where x = the weighted rank of the HRU general geology. The equations were derived by first correlating the span of the parameter ranges with the span of the ranks. Thus, the maximum and minimum parameter range values were set to the maximum and minimum geology rankings. A third point corresponding to approximately the midpoint parameter value was established for the mid-point (4.0) geology ranking. Initial parameter estimates were established for three gaged basins whose geology rankings were closest to the minimum, midpoint, and maximum rankings. Equations were fit to these points.

The objective function for estimates of base-flow percentages was defined as the average of the differences in base-flow percentages as simulated and as computed by PART. PART is a hydrograph-separation program described by Rutledge (1998). The objective function was minimized by manual adjustment of the parameters and final equations were fit to the three basin points. The calibrated base-flow percentages and associated errors are listed in table 6. Base-flow percentage errors ranged from -6.9 percent to 25.7 percent, and the average overall error is 3.6 percent. Tohickon Creek near Pipersville had the largest error at 25.7 percent. Tohickon Creek Basin also had the lowest percentage of base-flow yield of all the modeled basins at 32.5 percent as computed by PART. The basin is underlain by substantial areas of diabase. The capacity of diabase to store and transmit water is extremely low (Greenman, 1955). The generalized geology rankings used for

Table 6. Comparison of model-simulated and PART-derived (Rutledge, 1998) estimates of base flow as a percentage of total streamflow for streamflow-gaging stations in the Pennsylvania Highlands.

Basin_Name	U.S. Geological Survey streamflow-gaging station number	Predominant rock type	Base flow, percent		
			Simulated	PART	Error, percent
Little Lehigh Creek near Allentown, Pa.	01451500	Carbonate	76.7	83.6	-6.9
Tohickon Crk nr Pipersville, Pa.	01459500	Siliciclastic	58.2	32.5	25.7
Tulpehocken Crk nr Bernville, Pa.	01470779	Carbonate	82.7	85.1	-2.4
Manatawny Crk nr Pottstown, Pa.	01471980	Crystalline	69.5	69.0	.5
French Crk nr Phoenixville, Pa.	01472157	Crystalline	62.1	68.5	-6.4
Perkiomen Crk at E. Greenville, Pa.	01472198	Crystalline	62.7	67.9	-5.2
WBr Perkiomen Crk at Hillegass, Pa.	01472199	Crystalline	62.7	66.2	-3.5
Skippack Crk nr Collegeville, Pa.	01473120	Siliciclastic	53.1	43.4	9.7
WBr Brandywine Crk nr Honey Brook, Pa.	01480300	Crystalline	68.9	59.8	9.1
WBr Brandywine Crk at Coatesville, Pa.	01480500	Crystalline	67.6	66.3	1.3
Marsh Crk nr Glenmoore, Pa.	01480675	Crystalline	68.1	59.5	8.6
Quittapahilla Crk nr Bellegrove, Pa.	01573160	Carbonate	79.4	67.5	11.9
Conestoga River at Lancaster, Pa.	01576500	Crystalline	66.5	70.7	-4.2
Pequea Creek at Martic Forge, Pa.	01576787	Carbonate	83.6	71.5	12.1
Average of all basins					3.6

curve fitting of the smidx_coef and smidx_exp parameters did not account for these low-yielding areas, which explains the large overestimate of base-flow percentage for this basin.

Rainfall-Runoff Model Results

Data for the water-budget components—evapotranspiration, total streamflow, runoff, and base flow—were produced for three different model simulations. The simulations represented three different scenarios: average conditions during 1986–2001, maximum build-out under high-constraints development, and maximum build-out under low-constraints development. Results for the three simulation scenarios are presented by HUC 14 subwatershed in appendix 1.

All climatic inputs, surface-water and ground-water withdrawals by public water suppliers, and surface-water discharges were held or assumed constant for the simulations so that changes in the modeled water budget would be solely the result of changes in impervious area. Changes in impervious area were derived from estimates of future development scenarios compared to existing conditions.

Changes in self-supplied ground-water use were derived outside of the model from projected increases in population based on increases in the available housing resulting from high- and low-constraints development scenarios. Self-supplied ground-water withdrawals typically are from residential wells. Except for an estimated 20-percent consumptive use, these withdrawals were assumed to be returned to the same watershed through on-lot septic systems. The 20-percent consumptive-use estimates are reported in appendix 1. Withdrawals for public water supply may or may not be returned to the same watershed and are not reported.

Watershed Water Budgets

The percentage of total streamflow that is base flow was calculated from model-generated water budgets for each HUC 14 subwatershed using the 1986–2001 average climate and impervious-surface data and is summarized in figure 6. Model results indicate that, on average, base flow comprised 65 percent of total streamflow over the Pennsylvania Highlands Region (95 HUC 14 subwatersheds) during that period. The proportion of base flow in a stream is strongly dependent on the geology, soils, and impervious cover (or land use) in that watershed. In rocky areas with little or no sediment cover and (or) with soils of low permeability, the ground-water contribution to streamflow is small because ground-water storage capacity is minimal, infiltration and ground-water recharge are low, or both. The bedrock of the southeastern area of the Highlands mostly consists of shales and sandstones of low permeability. In conjunction with moderate to high degrees of development, these areas yield base-flow percentages less than 55 percent (fig. 6). Other areas where base flow accounts for less than 55 percent of streamflow are the more urbanized areas such as the Harrisburg metropolitan area near the

extreme western end of the Highlands. Watersheds with high base-flow percentages are in areas underlain by carbonate rocks, especially those areas with sinkholes and well-developed solution channels. In these area, a greater percentage of available precipitation, aided by the presence of sinkholes, infiltrates rather than runs off. Solution channels provide high ground-water storage capacity and high yields to base flow. Base flow accounts for more than 80 percent of total streamflow in many of the watersheds along the northern and southwestern boundary of the Pennsylvania Highlands (fig. 6). Carbonate bedrock typically underlies a substantial portion of these watersheds.

Build-Out Scenarios

The build-out scenarios were conducted by the RPA. The build-out analysis was initiated by identifying the existing developed land. The primary data sets used to determine built-up land were the NLCD 2001 for Pennsylvania (Yale School of Forestry & Environmental Studies, Highlands Regional Study, written commun., Jan. 14, 2008). Locations having the potential to be residentially developed were identified through an analysis of municipal zoning maps and ordinances (Yale School of Forestry & Environmental Studies, Highlands Regional Study, written commun., Jan. 14, 2008). The RPA study was concerned only with local zoning capable of accommodating single-family, detached residential development. The zoning build-out analysis essentially looked at land that is available for development and projected how much development can occur on that land under current zoning regulations (Yale School of Forestry & Environmental Studies, Highlands Regional Study, written commun., Jan. 14, 2008).

The build-out analysis was done under two conditions referred to as *low constraints* and *high constraints*, meaning constraints to development in order to preserve environmental or conservation values. The *low-constraints* scenario assumes minimal restrictions on development. The *high-constraints* scenario is presented as a high standard for protecting environmentally sensitive areas (Yale School of Forestry & Environmental Studies, Highlands Regional Study, written commun., Jan. 14, 2008).

For the water-resource analysis, RPA provided USGS with data on the total new acres of impervious cover under the full-zoning build-out. To obtain the new acres of impervious cover, RPA analyzed the relation between existing impervious data and current housing-unit (dwelling) data. First, all areas not spatially coincident with developed land use in the NLCD 2001 LULC data set were removed from the NLCD 2001 Impervious Surface Coverage. Next, a data set was created by extracting from the impervious-surface data only those areas within zoning districts that allowed housing units (residential, agricultural, and mixed-use districts). Using this data set, RPA calculated average impervious-surface coverage by 2000 U.S. Census Tract. A relation between percent average impervious-surface coverage and dwelling units per acre (derived from the U.S. Census data) at the tract level was developed using a simple linear regression.

Pennsylvania regression equation:

$$\text{Mean \% Impervious Surface Coverage} = 25.43 + 3.95 \times (\text{dwelling units/acre}) \quad (3)$$

RPA used the inverse of the minimum lot size per zoning locale to represent the maximum dwelling units per acre at build-out as input to the regression equations. The mean percent impervious for each zoning locale was then converted to a proportion and multiplied by the total acres of developable land within the district. For the Highlands overall, the low-constraints and high-constraints build-out scenarios increased impervious area by 143 and 119 percent, respectively.

The effect of low- and high-constraints development scenarios on the Pennsylvania Highlands water budgets was evaluated using the PRMS model. Projected increases in impervious surface cover and ground-water withdrawals are the factors driving the change in water-budget components between existing conditions (1986–2001) and the projected-development scenarios. The simulated water budgets show substantial change between existing conditions and the projected-development scenarios but minimal change between the high- and low-constraints development scenarios. Discussion in this report focuses on the low-constraints development scenario because it represents the worst-case conditions.

As the percentage of impervious area in a subwatershed increases depending on the build-out scenario, runoff increases, base flow decreases, total streamflow increases, and evapotranspiration decreases. The increase in impervious area, as projected by the low- and high-constraints build-out scenarios had, in general, a greater impact on the water budgets for the Pennsylvania Highlands HUC 14 subwatersheds than did the additional ground-water withdrawals (consumptive use) estimated from projected population growth. The average decrease in base flow under the low-constraints scenario is 10 percent, whereas the average decrease in base flow resulting from increases in consumptive use of self-supplied ground water is 0.6 percent. Actual decreases in base flow resulting from ground-water withdrawals will likely be greater than 0.6 percent (but much less than 10 percent) because public supply ground-water withdrawals also will increase under the low-constraints scenario.

As impervious area increases, runoff increases more than base flow decreases because of a reduction in evapotranspiration as well as recharge. The change in runoff, base flow, and ET resulting from increasing amounts of change in the impervious area in the model HRUs is shown in figure 7. The linear nature of the relations implies that changes in the water-budget components are directly proportional to the changes in the effective impervious surface up to the maximum change simulated, which is approximately 15 percent. To bring this into perspective, under a build-out scenario where the increase in effective impervious area approaches 15 percent, increases in runoff of 40 percent and decreases in base flow of 10 per-

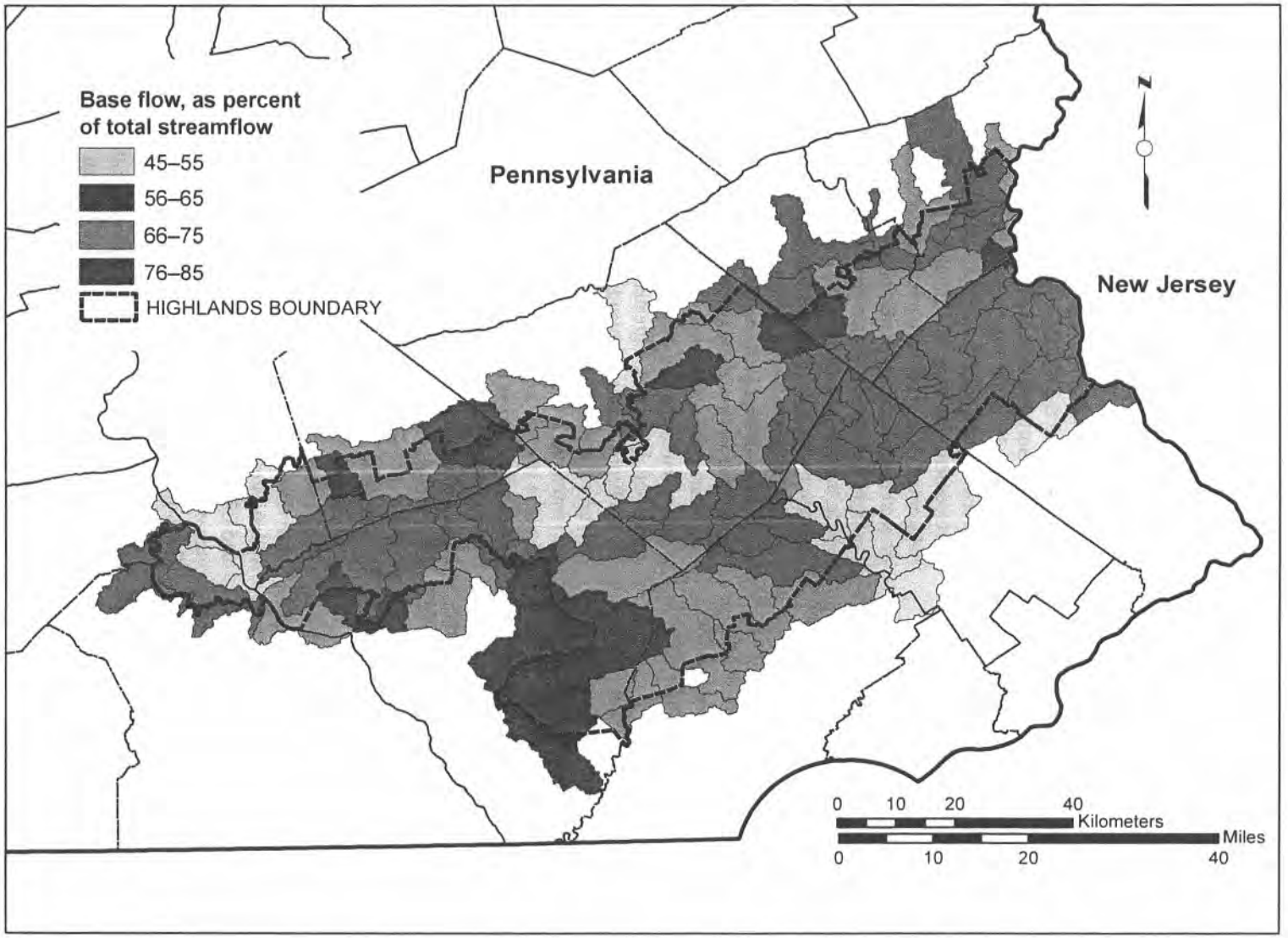

Figure 6. Base flow in the Pennsylvania Highlands HUC 14 subwatersheds, in percent averaged from 1986 through 2001.

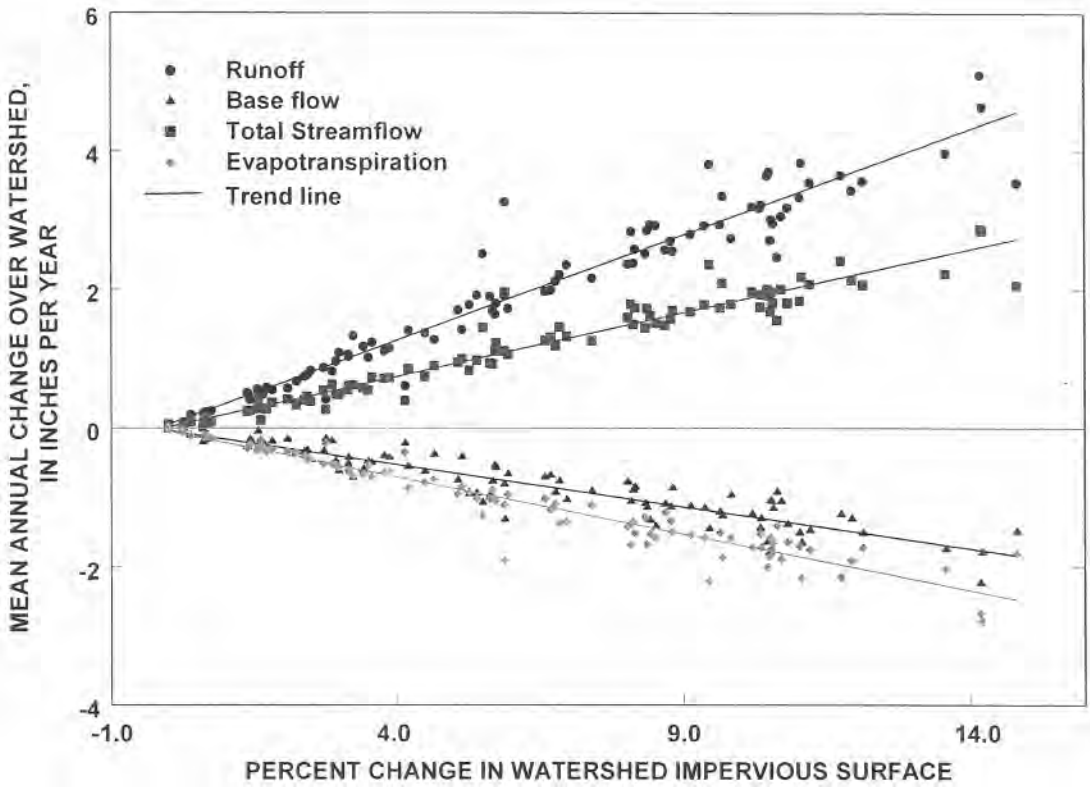

Figure 7. Streamflow characteristics and evapotranspiration in relation to percent change in effective impervious surface area as modeled for the Pennsylvania Highlands.

cent are likely. This implies, given similar climatic conditions, less water in streams during dry periods and higher peak flows during wet periods.

An important consideration in this analysis is that all impervious surfaces are considered 70 percent effective. As noted previously, other investigators have shown that effective impervious area in general increases with the level of development. A literature review by Brabec and others (2002) shows effective impervious values in the range of 70 percent occurring in high-density multi-family and commercial land-use categories. Given this observation and the generally low density of development existing in the Pennsylvania Highlands, a 70-percent effective value applied to all impervious areas under existing conditions is most likely too high. A lower effective impervious percentage would reduce the effect of impervious area on the water budget under the build-out scenarios. However, at the same time, the additional development expected under the build-out scenarios will increase both the total impervious area and the percent effectiveness over existing conditions. This change would, to an unknown degree, counter the effect using a lower or varying effective impervious percentage for existing conditions would have on the water budget. A fair accounting of these effects would require information on the distribution of impervious area under the build-out scenarios, which is not available.

On the basis of the increase of impervious surface area and the increase in ground-water withdrawals to meet projected population increases for the low-constraints build-out scenario, the HUC 14 subwatersheds with the greatest combined change in runoff and base flow (fig. 8) include the Frya Run Basin (HUC 14, 02040105140070), Saucon Creek Basin (HUC 14, 02040106080420), Cooks Creek Basin (HUC 14, 02040105170005), Tinicum Creek Basin (HUC 14, 02040105170055), Ironstone Creek Basin (HUC 14, 02040203060240), Mill Creek Basin (HUC 14, 02040203040240), Allegheny Creek Basin (HUC 14, 02040203050320), Pigeon Creek Basin (HUC 14, 02040203100220), East Branch Brandywine Creek Basin, Downingtown to headwaters (HUC 14, 02040205010240), Pequea Creek Basin, Watson Run to headwaters (HUC 14, 02050306120220), and the East Branch Octoraro Creek Basin, Valley Run to headwaters (HUC 14, 02050306180220). The combined increase in runoff and decrease in base flow is 5.5 inches or greater in these watersheds.

On the basis of the proposed population increase for the low-constraints build-out scenario and a 60 gallon per day per person water use, an additional 59.5 Mgal/d (million gallons per day) of self-supplied ground water were estimated withdrawn from aquifers underlying the subwatersheds. Of this, 18.9 Mgal/d would be used consumptively. The additional self-supplied ground-water withdrawals represent from less

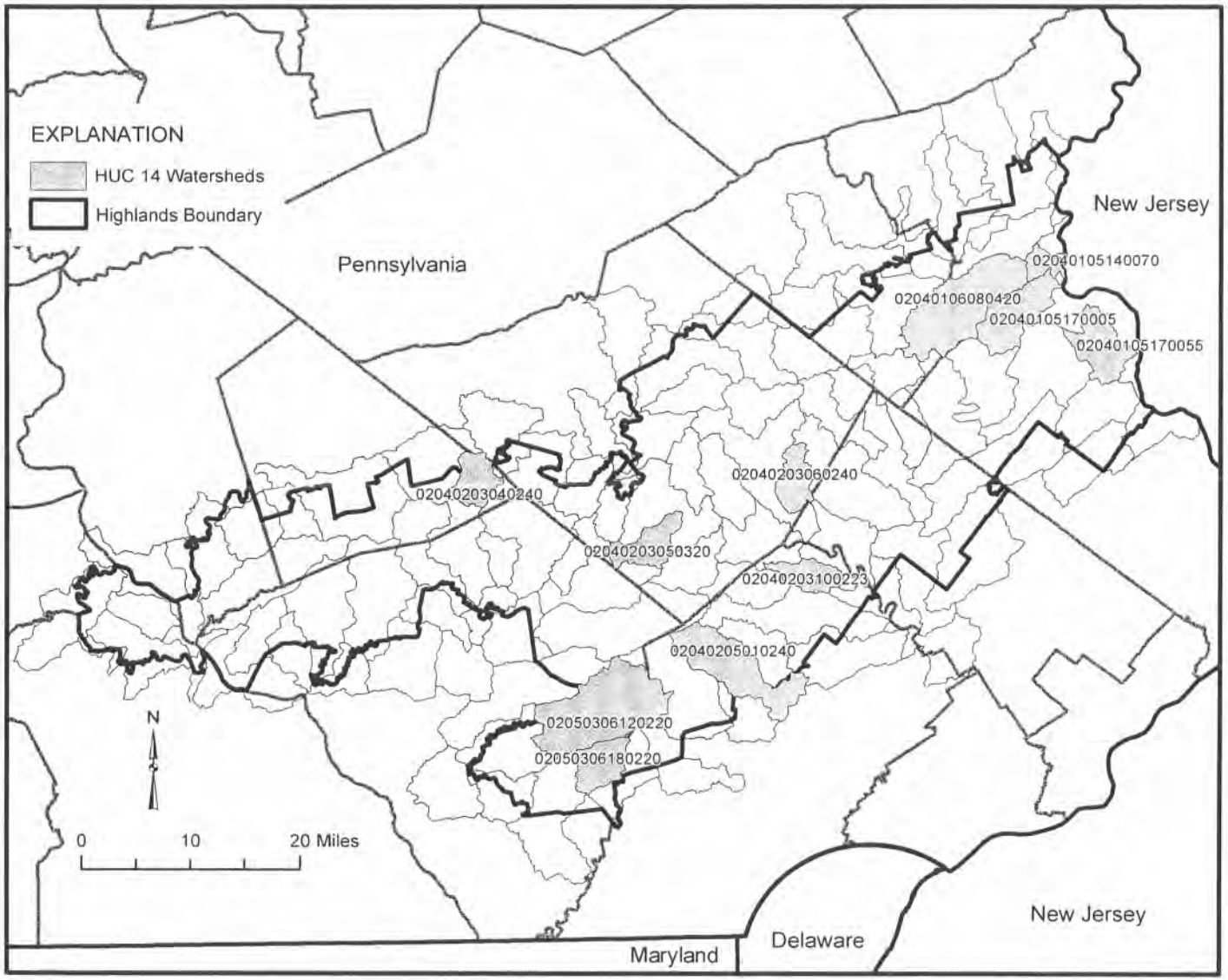

Figure 8. HUC 14 subwatersheds with the greatest combined change in runoff and base flow under the low-constraints build-out scenario.

than 0.1 to 11.5 percent (less than 0.1 to 2.3 percent consumptively) of the base flow for the HUC 14 subwatersheds. Under the low-constraints scenario, 34 HUC 14 subwatersheds show ground-water withdrawals exceeding 5 percent of base flow, and 4 subwatersheds show withdrawals exceeding 10 percent of base flow. The four subwatersheds with base-flow withdrawals exceeding 10 percent are in the Cocalico Creek, East Branch Octoraro Creek, East Branch Brandywine Creek, and Frya Run Basins.

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Appendix (on CD-Rom)

HUC 14 water budgets for three scenarios simulated for the Pennsylvania Highlands