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Simulation of Runoff and Reservoir Inflow for Use in a Flood-Analysis Model for the Delaware River, Pennsylvania, New Jersey, and New York, 2004-2006

Open-File Report 2010-1014

U.S. Department of the Interior
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Preface

This report describes a model, comprised of software and data files, for hydrologic simulation of the main-stem subbasin of the Delaware River. The performance of this model has been tested on several different computer systems and configurations. Future use, however, might reveal errors that were not detected in the test simulations. Users are requested to send notification of any errors found in this report or the model to:

Director
USGS Pennsylvania Water Science Center
215 Limekiln Road
New Cumberland, Pennsylvania 17070
dc_pa@usgs.gov

The latest version of the model and this report can be obtained using the Internet address below (accessed January 2010):

http://pa.water.usgs.gov/drbfam

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Conversion Factors, Datum, and Acronyms

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
square foot (ft^2)	0.09290	square meter (m^2)
square inch (in^2)	6.452	square centimeter (cm^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile [$(ft^3/s)/mi^2$]	0.01093	cubic meter per second per square kilometer [$(m^3/s)/km^2$]
gallon per minute (gal/min)	0.06309	liter per second (L/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
inch per hour (in/h)	0 .0254	meter per hour (m/h)
	Pressure	
atmosphere, standard (atm)	101.3	kilopascal (kPa)
bar	100	kilopascal (kPa)
inch of mercury at 60ºF (in Hg)	3.377	kilopascal (kPa)
pound per square inch (lb/in^2)	6.895	kilopascal (kPa)
	Density	
pound per cubic foot (lb/ft^3)	16.02	kilogram per cubic meter (kg/m^3)
pound per cubic foot (lb/ft^3)	0.01602	gram per cubic centimeter (g/cm^3)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:
°F=(1.8×°C)+32
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 North American Vertical Datum of 1988 (NAVD 88).
Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).
Altitude, as used in this report, refers to distance above the vertical datum.

Acronyms used in this report

COOP	Cooperative Climate Station
DEM	digital elevation model
DRBC	Delaware River Basin Commission
EST	Eastern Standard Time
GIS	geographic information system
GMT	Greenwich Mean Time
HEC	Hydrologic Engineering Center
HEC-DSS	USACE HEC Data Storage System
HEC-ResSim	USACE HEC Reservoir System Simulation program
HRU	hydrologic response unit
MARFC	Middle Atlantic River Forecast Center
MMS	Modular Modeling System
MPE	Multisensor Precipitation Estimate
NCDC	National Climatic Data Center
NED	National Elevation Dataset
NOAA	National Oceanic and Atmospheric Administration
NRCC	Northeast Regional Climate Center
NRMSE	normalized root mean square error
NWS	NOAA's National Weather Service
NYCDEP	New York City Department of Environmental Protection
OUI	Object User Interface
PRMS	Precipitation-Runoff Modeling System
STATSGO	State Soils Geographic Database
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey

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Abstract

A model was developed to simulate inflow to reservoirs and watershed runoff to streams during three high-flow events between September 2004 and June 2006 for the main-stem subbasin of the Delaware River draining to Trenton, N.J. The model software is a modified version of the U.S. Geological Survey (USGS) Precipitation-Runoff Modeling System (PRMS), 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. The PRMS model simulates time periods associated with main-stem flooding that occurred in September 2004, April 2005, and June 2006 and uses both daily and hourly time steps. Output from the PRMS model was formatted for use as inflows to a separately documented reservoir and river-routing model, the HEC-ResSim model, developed by the U.S. Army Corps of Engineers Hydrologic Engineering Center to evaluate flooding. The models were integrated through a graphical user interface.

The study area is the 6,780 square-mile watershed of the Delaware River in the states of Pennsylvania, New Jersey, and New York that drains to Trenton, N.J. A geospatial database was created for use with a geographic information system to assist model discretization, determine land-surface characterization, and estimate model parameters. The USGS National Elevation Dataset at 100-meter resolution, a Digital Elevation Model (DEM), was used for model discretization into streams and hydrologic response units. In addition, geospatial processing was used to estimate initial model parameters from the DEM and other data layers, including land use. The model discretization represents the study area using 869 hydrologic response units and 452 stream segments. The model climate data for point stations were obtained from multiple sources. These sources included daily data for 22 National Weather Service (NWS) Cooperative Climate Station network stations, hourly data for 15 stations from the National Climatic Data Center, hourly data for 1 station from the NWS Middle Atlantic River Forecast Center records, and daily and hourly data for 7 stations operated by the New York City Department of Environmental Protection. The NWS Multisensor Precipitation Estimate data set for 2001-2007 was used for computing daily precipitation for the model and for computing hourly precipitation for storm simulation periods.

Calibration of the PRMS model included regression and optimization algorithms, as well as manual adjustments of model parameters. The general goal of the calibration procedure was to minimize the difference between discharge measured at USGS streamgages and the corresponding discharge simulated by the model. Daily streamflow data from 35 USGS streamgages were used in model calibration. The streamflow data represent areas draining from 20.2 to 6,780 square miles.

The PRMS model simulates reservoir inflow and watershed runoff for use as input into HEC-ResSim for the purpose of evaluating and comparing the effects of different watershed conditions on main-stem flooding in the Delaware River watershed draining to Trenton, N.J. The PRMS model is useful as a planning tool to simulate the effects of land-use changes and different antecedent conditions on local runoff and reservoir inflow and, as input to the HEC-ResSim model, on flood flows in the main stem of the Delaware River.

Introduction

Major flooding occurred in the Delaware River Basin in September 2004, April 2005, and June 2006. To evaluate the impact of reservoir levels and other factors on flooding, the Delaware River Basin Commission (DRBC), U.S. Geological Survey (USGS), U.S. Army Corps of Engineers (USACE) Hydrologic Engineering Center (HEC), and National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS) developed a Delaware River Flood-Analysis Model. The Flood-Analysis Model has two components, a rainfall-runoff watershed model, the PRMS model, and a reservoir operation and streamflow-routing model, the HEC-ResSim model.

Purpose and Scope

This report describes the rainfall-runoff watershed model component of the Flood-Analysis Model for the Delaware River above Trenton, N.J. The rainfall-runoff model software is a modified version of the USGS Precipitation-Runoff Modeling System (PRMS) (Leavesley and others, 1983; Leavesley and Stannard, 1995; Leavesley and others, 2005; Markstrom and others, 2008). This rainfall-runoff model simulates overland flow, groundwater flow, and streamflow to be used as inputs of reservoir inflows for 13 reservoirs (table 1, fig. 1), local inflows, and unregulated tributary flows for use in a reservoir and river routing model, the HEC-ResSim model, for the comparative analyses of different watershed conditions on main stem flows. The HEC-ResSim component of the Flood-Analysis Model is documented in a separate report. The PRMS model may be used as a planning tool to evaluate the effects of watershed conditions on runoff and, in combination with HEC-ResSim, on flows in large rivers and the main stem of the Delaware River above Trenton, N.J. during floods. The PRMS model was not developed as a forecasting tool for realtime prediction of flooding.

This report describes the software, data sources, construction, and calibration of the rainfall-runoff model of the Delaware River Basin draining to Trenton, N.J. The model simulates time periods associated with main-stem flooding that occurred in September 2004, April 2005, and June 2006.

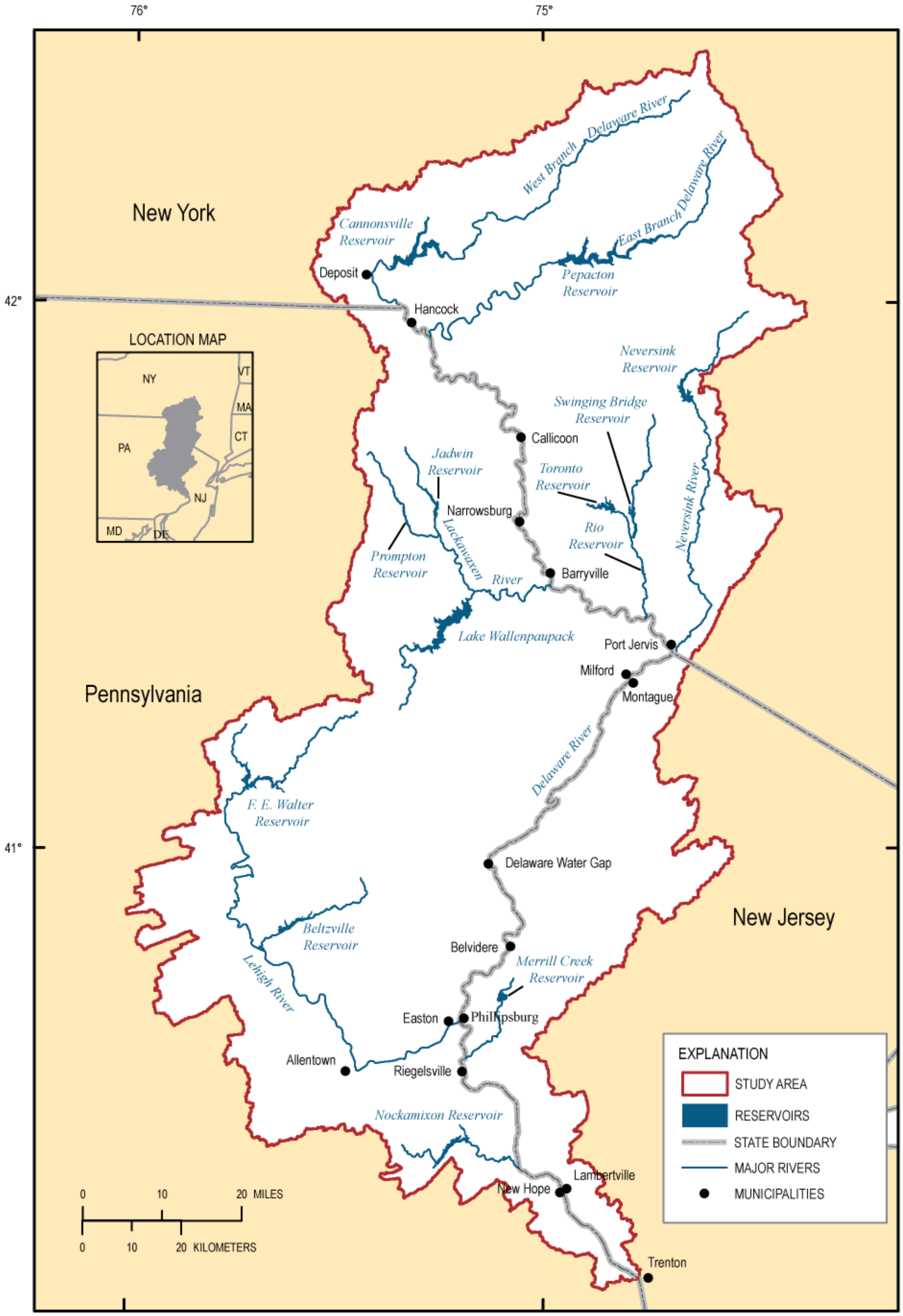

Figure 1. Location of the Delaware River main-stem subbasin and selected reservoirs, Pennsylvania, New Jersey, and New York.

Table 1. Selected reservoirs in the Delaware River mainstem subbasin, Pennsylvania, New Jersey, and New York (data from Delaware River Basin Commission).

[FA, flow augmentation; FL, flood-loss reduction; P, hydroelectric power generation; WS, water supply; WSA, water supply primarily for flow augmentation]

Reservoir	Purpose	Storage (million gallons)	Location (stream, county, state)
Cannonsville	WS, FA	96,726	West Branch Delaware River, Delaware, N.Y.
Pepacton	WS, FA	143,701	East Branch Delaware River, Delaware, N.Y.
Neversink	WS, FA	35,466	Neversink River, Sullivan, N.Y.
Mongaup System: Rio, Swinging Bridge, Toronto	P	15,314	Mongaup River, Sullivan, N.Y.
Lake Wallenpaupack	P	29,813	Wallenpaupack Creek, Wayne, Pa.
Prompton	FL	6,614	West Branch Lackawaxen River, Wayne, Pa.
Jadwin	FL	7,983	Dyberry Creek, Wayne, Pa.
Francis E. Walter	FL	35,190	Lehigh River, Luzerne and Carbon, Pa.
Beltzville	WSA FL	12,978 8,797	Pohopoco Creek, Carbon, Pa.
Merrill Creek	WSA	15,640	Merrill Creek, Hunterdon, N.J.
Nockamixon	WS[1]	11,990	Tohickon Creek, Bucks, Pa.

[1] Used for flow augmentation during drought emergencies.

Previous Studies

A number of previous studies provide background information on the Delaware River and its watershed. Delaware River Basin Commission (2008a) summarizes the status of the watershed as of 2008, including flooding and water-supply issues. Ayers and others (1994) describe potential effects of climate change on water resources in the basin. Fischer and others (2004) assess the water quality in the basin. Sloto and Buxton (2005) compute water budgets for a small subbasin of the Delaware River where development is occurring apace. Paulachok and others (2000) describe hydrologic conditions during drought in 1998-1999. Previously, Hirsch (1981) analyzed the probabilistic impact of reservoir operations on water-resource availability during drought.

Recent flooding in the Delaware River Basin is described in several studies. Brooks (2005) describes the flood of September 18-19, 2004, in the upper Delaware River Basin. Effects of the flood of April 2005 are described by Suro and Firda (2006) for the Neversink River Basin and by Reed and Protz (2007) for the main-stem Delaware River. Suro and others (2009) describe the flooding of June 26-29 in parts of the Delaware River Basin and other basins in New York. Online summaries of flooding during June 2006 are provided by the Delaware River Basin Commission (2008b) and the U.S. Geological Survey (2008b).

The magnitude and recurrence of floods have been evaluated by many previous authors and updated as the period of record has been extended. Schopp and Firda (2008) evaluate flood frequency and magnitude for the main-stem Delaware River to Trenton, N.J., updating the statistical model of flood recurrence using data from the three recent flood events. Roland and Stuckey (2007) present flood-frequency models for selected smaller streams in the basin.

Rainfall-runoff and streamflow models have previously been developed for the study area. Flippo and Madden (1994) calibrated a streamflow-routing model for the Delaware River, with an emphasis on low-flow simulations. Chepiga and others (2004) developed a statistically based model of long-term runoff and water quality for the basin. Middle Atlantic River Forecast Center (MARFC) (2006, 2007) simulated the impact of reservoir-void changes on downstream flood levels using the NWS flood-forecast model for the Delaware River, a model used operationally for flood forecasting.

Rainfall-runoff and streamflow models have also been developed for smaller watersheds within the study area. Tolson and Shoemaker (2007) developed, calibrated, and validated a model of daily streamflow into Cannonsville Reservoir on the West Branch Delaware River. Kalin and Hantush (2006) compared the use of radar and rainfall data for modeling daily and monthly flows for the Pocono Creek watershed in Monroe County, Pa.

A daily reservoir model for the Delaware River above Trenton, OASIS (HydroLogics, Inc., 2002), has been developed to simulate reservoir releases and downstream flows. Quinodoz (2006) describes the use of OASIS to support basin management and planning. Bovee and others (2007) used OASIS to develop a model for evaluation of fish habitat in stream reaches in the upper part of the basin, including a model of stream temperature.

Description of Study Area

The study area is the watershed of the Delaware River in the states of Pennsylvania, New Jersey, and New York that drains to Trenton, N.J. (fig. 1). The watershed is delineated on the basis of the area draining to the USGS streamgage on the Delaware River at Trenton, N.J. (USGS 01463500). This is the most downstream streamgage on the main stem that is not normally affected by tides. The watershed area above the Trenton streamgage is 6,780 mi^2. The river length from the confluence of the West Branch Delaware River and the East Branch Delaware River at Hancock, N.Y., to Trenton, N.J., is approximately 200 mi. Watershed characteristics are briefly summarized in this report; additional detailed descriptions are provided by previous investigators, including Schopp and Firda (2008), Ayers and others (1994), Parker and others (1964), Fischer (1999), and Fischer and others (2004).

The Delaware River Basin has a temperate climate; seasonal and average yearly variations generally reflect variations in topography (Jenner and Lins, 1991). Average yearly temperature ranges from about 45°F in the north to 56°F in the south. Winter (December – February) monthly average temperature is slightly above freezing in the south and about 25°F in the north. The summer (June – August) average ranges from almost 80°F in the south to 70°F in the north.

Average annual precipitation ranges from 50 in. in the north to 42 in. in the south and is typically distributed evenly throughout the year (Jenner and Lins, 1991). The number of days with precipitation generally increases from the southern to the northern part of the basin, whereas the average intensity of precipitation for days when precipitation falls generally decreases from the southern to the northern part. Variation in mean annual precipitation within the basin is primarily related to elevation changes; higher precipitation amounts are related to higher elevations (Ayers and others, 1994).

Soils, vegetation, and topography differ considerably in the basin (Parker and others, 1964). The basin lies in four physiographic provinces (Parker and others, 1964). In the southern part of the study area, the topography varies from the rolling hills of the Piedmont Physiographic Province to a series of parallel ridges, oriented northeast-southwest, in the New England Physiographic Province. These two provinces are characterized by relatively thin, clayey-loam soils, and streams respond quickly to rainfall. About one-third of the southern part of the study area is forested, primarily with hardwoods.

In the northern part of the study area, the Appalachian Plateaus and Valley and Ridge Physiographic Provinces are characterized by mountainous topography. Hillslopes are steep and covered by well-drained soils. Streamflow response to rainfall is delayed compared to the southern part of the study area. The northern part is the only part of the basin where snow accumulation is substantial in most years and the only part that once was glaciated. The northern part has numerous lakes and is mostly forested in hardwoods.

The Delaware River Basin is a vital water resource for the Nation. The daily average water use in the basin is about 4 billion gallons, more than one-half of which is for power generation. Public supply, industrial supply, and irrigation account for about 25, 15, and 1 percent, respectively, of the total water use. The Delaware River supplies large quantities of water to two of the largest metropolitan areas in the Nation—New York City and Philadelphia (Fischer and others, 2004). Approximately 620 Mgal/d is exported from the basin to New York City, and another 100 Mgal/d is exported to northeastern New Jersey. The water-management system in the basin includes many surface reservoirs used for multiple purposes, including water supply, flow augmentation, and flood mitigation (table 1). Many of these reservoirs are also used to enhance fish and wildlife habitat and increase recreational opportunities (Delaware River Basin Commission, 2008a).

Precipitation-Runoff Modeling System

The USGS PRMS (Leavesley and others, 1983; Leavesley and Stannard, 1995) software is a modular, physically based, distributed-parameter modeling system developed to evaluate the impacts of climate, topography, geology and land use on surface-water runoff and general basin hydrology. In PRMS, each component of the hydrologic system is simulated with known physical laws or empirical relations formulated on the basis of measurable watershed characteristics. The distributed-parameter and watershed-partitioning features of PRMS are designed to account for the spatial variation in watershed characteristics. The watershed is delineated into a series of contiguous spatial units, called hydrologic response units (HRUs), where the slope, land use, soil, geology, and precipitation distribution are similar. HRUs produce and receive flow to and from each other, to the atmosphere, and to the drainage network consisting of stream segments and lakes. Each HRU is considered homogeneous as to hydrologic response and is instantaneously and fully mixed. Areally weighted averages are computed for each characteristic that varies spatially within an individual HRU (Markstrom and others, 2008).

PRMS Modules

PRMS simulates a watershed as an interconnected series of reservoirs that represent a volume of finite capacity within each HRU. These reservoirs include water in the canopy, impervious area, snowpack, pervious portion of the soil zone—up to field capacity of the soil to rooting depth (capillary reservoir), pervious and impervious portions of the soil zone—between field capacity and total soil saturation (gravity reservoir), and water stored below the rooting zone—used to simulate groundwater flow (groundwater reservoir). The gravity reservoir can be split into two reservoirs to simulate a relatively faster interflow response (preferential flow) to a precipitation or snowmelt event that is due to the presence of macropores within the soil zone. PRMS simulates groundwater flow and storage as a combined, finite-volume series of three reservoirs—the capillary, gravity, and preferential-flow reservoirs. Flow to and from each reservoir is in the form of evaporation from the canopy and impervious areas, sublimation from the snowpack, evapotranspiration from the capillary reservoir, interflow and recharge from the gravity reservoir, and groundwater flow from the groundwater reservoir. Overland runoff is simulated on the basis of the antecedent conditions of the impervious, capillary, and gravity reservoirs. A cascading-flow procedure is used in PRMS (Markstrom and others, 2008) to simulate overland flow, interflow, and groundwater discharge in a cascading pattern between HRUs and then to the drainage network. PRMS simulates flow in the stream-channel network as the sum of inflows to each stream segment without routing when using a time step of 1 day. For hourly simulation, an implicit kinematic wave algorithm is used for streamflow routing.

The 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. On the basis of the issues being investigated, data availability, and appropriateness of an algorithm to a particular watershed, modelers can customize PRMS by selecting the most appropriate modules for a given application. The modules selected for this study are listed in table 2 in computation order. New modules were added to PRMS for this study to 1) read preprocessed precipitation and air-temperature data by HRU, 2) generate specially formatted output for use as input to the HEC-ResSim model, and 3) simulate hourly snowpack processes using the NWS SNOW-17 model.

The PRMS modules, the HEC Data Storage System (HEC-DSS) library, and Modular Modeling System (MMS) utilities are compiled and linked to generate the model software used for rainfall-runoff simulation. PRMS modules are a group of subroutines that simulate a particular hydrologic or data-handling process. The HEC-DSS library and MMS utilities are not described in detail here. The HEC-DSS library (U.S. Army Corps of Engineers, Hydrologic Engineering Center, 2006) consists of a set of routines that enable retrieval and storage of input and results. The MMS utilities (Leavesley and others, 1996, 2005) are similar to the HEC-DSS library in that they provide routines to read input and write output from a model simulation. In addition, the MMS utilities provide the means to access results from modules to be input to other modules. PRMS uses the internal data structure of MMS to make input data and model states and fluxes available between PRMS modeling components.

Table 2. Precipitation-Runoff Modeling System (PRMS) modules used for the Delaware River main-stem subbasin, Pennsylvania, New Jersey, and New York.

[HRU, hydrologic response unit; GWR, groundwater reservoir]

PRMS model module	PRMS module ID	Description	Reference
basin_prms	1	Computes shared watershed-wide physical parameters used by other modules and provides consistency checks of various input parameters	Markstrom and others, 2008
cascade_prms	2	Computes the routing order of cascading flow between HRUs and GWRs and performs consistency checks of the cascading parameters.	Markstrom and others, 2008
obs_prms	3	Reads and makes available observed precipitation, temperature, and solar-radiation data from specified measurement stations	Markstrom and others, 2008
climate_hru_prms	4	Reads and makes available NEXRAD precipitation data and temperature data preprocessed by HRU	Appendix
ddsolrad_hru_prms	5	Distributes solar radiation to each HRU and estimates missing solar-radiation data using a maximum temperature per degree-day relation	Markstrom and others, 2008
potet_jh_prms	6	Determines whether current time period is one of active transpiration and computes the potential evapotranspiration using the Jensen-Haise formulation (Jensen and others, 1969)	Markstrom and others, 2008
intcp_prms	7	Computes volume of intercepted precipitation, evaporation from intercepted precipitation, and throughfall that reaches the soil or snowpack	Markstrom and others, 2008
snowcomp_prms	8	Initiates development of a snowpack and simulates snow accumulation and depletion processes using an energy-budget approach for daily time steps	Markstrom and others, 2008
srunoff_smidx_casc	9	Computes Hortonian surface runoff and soil infiltration for each HRU using a non-linear variable-source-area method and partitions precipitation and snowmelt to the pervious and impervious portions of each HRU allowing for cascading flow and computed evaporation from imperious portions of each HRU for 24-hour time steps	Markstrom and others, 2008
grnampt_infil_prms	10	Computes soil infiltration for each HRU using a Green and Ampt method and partitions precipitation and snowmelt to the pervious and impervious portions of each HRU allowing for cascading flow and computed evaporation from imperious portions of each HRU for sub-daily time steps	U.S. Geological Survey, 1992a
krout_ofpl_prms	11	Computes Hortonian surface runoff for each HRU using a modified kinematic routing method for each HRU allowing for cascading flow for sub-daily time steps	U.S. Geological Survey, 1992c
soilzone_prms	12	Computes inflows to and outflows from soil zone of each HRU and includes inflows from soil infiltration and upslope HRUs, and outflows as evapotranspiration and recharge and interflow and Dunnian surface runoff to down-slope HRUs and the drainage network	Markstrom and others, 2008
gwflow_casc_prms	13	Sums inflow to groundwater reservoirs and computes outflow to the drainage network allowing for cascading flow	Markstrom and others, 2008
krout_chan_prms	14	Routes flow in the drainage network using various Kinematic routing schemes for sub-daily time steps	U.S. Geological Survey, 1992b
strmflow_prms	15	Computes streamflow as the sum of overland runoff, interflow, and groundwater flow for daily time steps	Markstrom and others, 2008

Table 2. Precipitation-Runoff Modeling System (PRMS) modules used for the Delaware River main-stem subbasin, Pennsylvania, New Jersey, and New York.—Continued

[HRU, hydrologic response unit; GWR, groundwater reservoir]

PRMS model module	PRMS module ID	Description	Reference
subbasin_prms	16	Computes streamflow as the sum of overland runoff, interflow, and groundwater flow for subbasins within a watershed	U.S. Geological Survey, 2007b
local_flow_drbc	17	Sums and outputs of overland runoff, interflow, and groundwater flow to hard-coded points (reservoirs and stream/river segments) within the Trenton basin to an HEC DSS file for use as input to HEC-ResSim. Also accumulates and outputs flows below non-modeled reservoirs for use in calibration.	Apppendix
hru_sum_prms	18	Computes daily, monthly, yearly, and total flow summaries of volumes and flows for each HRU	Markstrom and others, 2008
basin_sum_prms	19	Sums values for daily, monthly, yearly, and total flow summaries of volumes and flows for all HRUs	Markstrom and others, 2008
snow17_st	20	Computes snow accumulation and ablation for storm mode	Appendix

Model Documentation and Previous Applications

Documentation for the modeling system is available in the PRMS manual (Leavesley and others, 1983) and the GSFLOW manual (Markstrom and others, 2008). GSFLOW is a coupled groundwater and surface-water flow model that uses PRMS for watershed computations. The GSFLOW manual provides the most up-to-date description for the majority of the simulation processes used in the PRMS model used in this study. PRMS and the parameterization methods used here have been used in numerous other applications, including the effects of urbanization on the spatial distribution of groundwater recharge (Vaccaro, 1992; Steuer and Hunt, 2001); water-resources management and forecasting (Fulp and others, 1995; Wilby and others, 1999; Berris and others, 2001; Mastin and Vaccaro, 2002; Hay and others, 2002; Hay and Clark, 2003; Clark and Hay, 2004; Yeung, 2005); simulation of sediment production for semi-arid watersheds (Rankl, 1987); heat and water transfer for seasonally frozen soils (Emerson, 1991); use of radar data to specify rainfall input for flood simulation (Yates and others, 2000); streamflow and wetland storage (Vining, 2002); and flow-frequency characteristics (Olson, 2002).

Hourly Simulation Mode

PRMS was used with a daily time step for simulation of antecedent conditions (daily mode) and automatically switched to an hourly time step for simulation of storms (storm mode). This approach is computationally efficient for the relatively slow changes that occur under normal conditions between storms and provides sufficient detail and flood-wave simulation during storms.

Flow routing in streams during storm mode is simulated through a kinematic wave approach (Leavesley and Stannard, 1995; Yates and others, 2000). Runoff components are cascaded from HRU to HRU in the downstream direction, until the runoff enters a stream channel or lake. Channel flow is accumulated and kinematically routed to downstream junctions and through the drainage network. The implicit finite-difference option was used for the kinematic-wave flow routing, and the module parameters were identified by calibration.

Snowmelt

PRMS uses a daily energy-balance model to compute melt and runoff from snow for daily time steps (Leavesley and others, 1983). For storm mode, PRMS was modified to use the SNOW-17 algorithm from the River Forecast System of NOAA’s NWS (Anderson, 2006). This model is computationally efficient and uses hourly input data available for the study area, specifically precipitation and air temperature. This model incorporates the diurnal variation of radiation and other processes that control snowmelt through an approximate model that is based on air temperature. The basis of the SNOW-17 algorithm and its parameters are described in detail by Anderson (2006). Additional information about SNOW-17 algorithms is provided in the appendix.

Output for Reservoir Model

PRMS was modified for this study to prepare data needed for simulation of reservoirs and streamflow routing downstream of reservoirs in the watershed. The USACE HEC has developed a general-purpose reservoir-simulation model, HEC-ResSim (U.S. Army Corps of Engineers, Hydrologic Engineering Center, 2007), and has developed a reservoir model for the Delaware River. Hourly runoff to reservoirs and local runoff to streams downstream of modeled reservoirs are computed by PRMS and used as input for HEC-ResSim. HEC-ResSim computes discharge from reservoirs and routes this flow, accumulating local runoff and tributary inflow downstream from modeled reservoirs.

The output data provided from PRMS for use in HEC-ResSim are the time series of streamflow and local runoff into reservoirs and local runoff and tributary inflow for streams below modeled reservoirs. These PRMS output data are written to a HEC-DSS formatted file (trenton.dss). The HEC-DSS file format is a standard binary format developed by the HEC for storage of water-resources time-series data and is used for input for HEC-ResSim. The HEC-DSSVue program (U.S. Army Corps of Engineers, Hydrologic Engineering Center, 2006) is available for viewing and working with data stored in HEC-DSS files. Incremental flows, which do not include flows simulated at headwater streamgages, are also provided in the DSS file for optional use with the HEC-ResSim model for simulations in which observed flows at the headwater streamgages can be used instead of simulated flows at those stations. Additional information about the modifications for preparing HEC-ResSim data is provided in the appendix.

Use of Measured Reservoir Discharge

Reservoirs in the watershed are not simulated with PRMS, because those computations are conducted in the HEC-ResSim component of the Flood-Analysis Model. However, calibration of PRMS for local flows downstream of the reservoirs is based on comparison between simulated and measured streamflow, which includes the contributions of discharges from reservoirs. PRMS was modified to use measured reservoir discharges as the upstream inflow for simulation of downstream flows. Thus, the simulated flow at downstream streamgages is a combination of the measured discharge from the reservoir, routed to the streamgage, and local flows. This procedure allowed calibration of the model parameters that control the local flows downstream of the reservoirs.

The local flows from PRMS are used as input for HEC-ResSim. However, HEC-ResSim simulates the reservoirs and produces reservoir outflows as an output of the simulation on the basis of input data controlling the operations of the reservoirs. Thus, the use of measured reservoir outflows in the PRMS model calibration does not affect the simulated outflow from reservoirs in HEC-ResSim. Additional manual calibration of PRMS used simulated downstream flows from the HEC-ResSim model to improve the flow volume match.

User Interface

User interaction with the Flood-Analysis Model is through a graphical user interface developed using the Object-User Interface (OUI) (Markstrom and Koczot, 2008). This interface allows the user to view PRMS input, to run the model components, and to view model output using a map-based scheme. The OUI software is integrated with two open-source, public-domain software packages, GeoTools (*http://www.geotools.org/*) sponsored by the Open Source Geospatial Foundation and National Aeronautics and Space Administration (NASA) World-wind (*http://worldwind.arc.nasa.gov/java/*), for geospatial processing and visualization, respectively.

The Flood-Analysis Model user interface is written using OUI and allows the user to change physical and simulation control parameters, including specifying input files and the time period for simulation, and to select output written to files and graphs. A brief guide to the user interface for the Flood-Analysis Model is provided online at *http://pa.water.usgs.gov/drbfam*. More detailed instructions on the functionality and customization of OUI are provided by Markstrom and Koczot (2008).

Model Development

The PRMS model consists of the software, described in the previous section, and data input required for rainfall-runoff simulation. This section describes the procedures used to prepare input for, or parameterize, PRMS.

A geospatial database was created for use with a geographic information system (GIS) to assist model discretization, to determine land-surface characterization, and to estimate PRMS model parameters. The combination of the GIS database and standard spatial processing techniques, similar to previously modeled watersheds (Battaglin and others, 1993; Jeton, 2000; Jeton and others, 1996), allowed the spatial variations of basin characteristics to be documented and objectively analyzed. All data sets in the database are in the same Cartesian coordinate system: Universal Transverse Mercator (UTM), zone 18 with NAD 83 as the horizontal control datum.

Elevation Data and Watershed Discretization

Topography, or altitude change on the land surface, is a primary factor in the distribution and rates of surface runoff. Hence, a primary input for PRMS is a digital elevation model (DEM) of the study area. For this study, the USGS National Elevation Dataset (NED) (U.S. Geological Survey, 2007a) at 100-m resolution was used for the Delaware River Basin draining to Trenton, N.J. The DEM was pre-processed to specify locally low elevations at known stream locations in order to improve the match between known stream locations and those generated by automatic processing of the DEM.

A PRMS model uses the concept of partitioning a watershed into spatial units on the basis of watershed characteristics such as elevation, slope, aspect, vegetation type, soil type, land use, and precipitation distribution. Initially, the watershed is delineated into stream segments with a minimum flow accumulation as determined by a GIS analysis. The DEM was processed using automated techniques suggested by the GIS Weasel (Viger and Leavesley, 2007) to create flow-direction and flow-accumulation raster data sets that produced an artificial stream raster on the basis of a selected maximum number of contributing cells that totaled approximately 15 mi^2. This stream raster was manually edited to include selected elevation breaks in the DEM using analytical hillshading as a guide. These stream segments were then edited to represent the points at which runoff can be calibrated, at selected USGS streamgage locations. The stream network was also split by the outline of the 13 simulated reservoirs and where very long stream segments might produce instability in computing streamflow using the implicit, finite-difference kinematic routing scheme used for sub-daily stream routing.

An iterative procedure was used to discretize the watershed into HRUs and link those HRUs to a computational stream network. HRUs were initially generated using the DEM for the study area. The edited stream raster was then used to delineate the initial stream-segment contributing areas, or one-plane HRUs. The separate contributing surface areas to the left and right bank of each stream segment, two-plane HRUs, are required for storm-mode streamflow routing. These two-plane HRUs were created by using the stream raster and the DEM to determine the longest flow path to split the one-plane HRU into left- and right-bank drainages. After two-plane HRUs were converted from raster-format data into vector-format data, a spatial-join process was used to combine the reservoir polygons with the two-plane HRUs. A map of the reservoirs was overlain on the original HRUs, and simulated reservoirs were treated as a special type of HRU, a lake HRU. Manual editing was done as the final step to remove small-area HRUs or merge them into an adjacent, hydrologically similar HRU. The PRMS model of the Delaware above Trenton is composed of 869 HRUs and 452 stream segments (fig. 2).

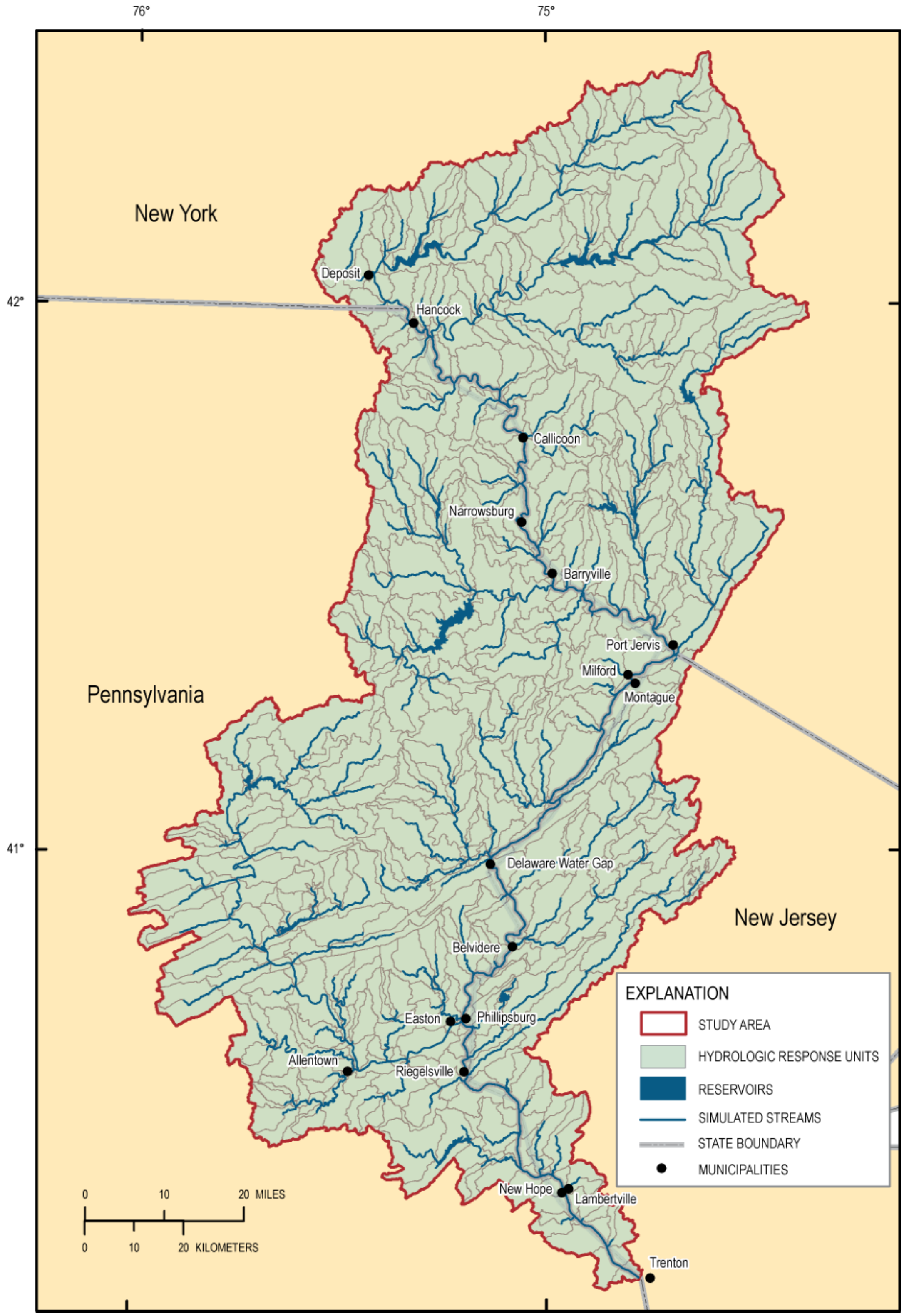

Figure 2. Location of hydrologic response units and simulated stream reaches for the Delaware River main-stem subbasin, Pennsylvania, New Jersey, and New York.

The GIS Weasel also determined HRU-specific indices describing connectivity of HRUs with the stream network. The HRU responses were grouped by stream segments specific to each subbasin, and flow was routed through the stream-segment units in a downstream order, enabling output from the model to provide estimates of flow at any stream segment.

Watershed Characteristics Data

PRMS model parameters related to watershed properties controlling runoff were assigned to the discretized model, HRUs and streams, by processing available GIS coverages of soils, elevation, geology, land use, and other characteristics. These initial parameters were subsequently adjusted, in some cases, during model calibration. The parameterization methods used include those documented by Viger and Leavesley (2007), Battaglin and others (1993), Jeton (2000), and Koczot and others (2005). Additional selected parameterization methods recently developed for modeling runoff in Connecticut were also used (D.M. Bjerklie, U.S. Geological Survey, written commun., May 11, 2009).

Digital spatial data were collected for the study in raster format (a gridded data structure made of rows and columns) and vector format (discrete coordinates that can be used as points or connected to create lines and polygons). The digital data included elevation, generalized geology, land cover, and soils. The sources for the spatial data included the USGS NED for elevation (U.S. Geological Survey, 2007a) where slope and aspect calculations were derived using GIS software ArcGIS version 9.2; state geology data from New Jersey (New Jersey Department of Environmental Protection, 1996), New York (New York State Museum/New York Geological Survey, 1999), and Pennsylvania (Pennsylvania Department of Conservation and Natural Resources, 2001); land cover and impervious surface data from the 2001 National Land Cover Database (Multi-Resolution Land Characteristics Consortium, 2001); and soils data originally from the State Soil Geographic (STATSGO) Database (Soil Survey Staff, 1994; Natural Resources Conservation Service, 2006) and further processed with value-added soil characteristics (Miller and White, 1998). Selected reclassification tables (Viger and Leavesley, 2007) were used with land-cover data to assist in refining the HRU characteristics. The sources of values for selected distributed PRMS model parameters are described in table 3, along with ranges of values used. Nondistributed parameters that apply to the entire model are described in table 4.

Table 3. Source of parameter values for selected model hydrologic response unit (HRU) distributed parameters for the Delaware River main-stem subbasin, Pennsylvania, New Jersey, and New York (modified from Jeton, 2000; Koczot and others, 2005).

[CAL, parameters that (a) cannot be estimated from available data and are adjusted during calibration or (b) have initial estimates from measured or published data that were adjusted during calibration; DEF, parameters that are considered constant, as provided by Leavesley and others (1983); LIT, obtained from the literature as estimated or empirical estimates (Black, 1996, table 4-1, p. 93); GIS, computed in geographic information system from digital coverages; COM, computed from climatological data or other measured data]

Model parameter	Description of model parameter	Range of values	Source of values	PRMS module ID[1]
carea_max	Maximum area contributing to surface runoff (decimal percent)	0.036–0.796	CAL	9
chan_alpha	Kinematic routing parameter "a" for each channel segment	0.076–0.693	CAL	14
chan_cmp	Kinematic routing parameter "m" for each channel segment	1.67	DEF	14
chan_rough	Roughness parameter for each channel segment	0.05	LIT	14
cov_type	Vegetation cover type (developed-water-open, grasses-shrubs, mixed forest, coniferous forest)	Developed-water-open, grasses-shrubs, mixed forest, coniferous forest	GIS	7, 8,12
covden_sum	Vegetation cover density for summer (decimal percent)	0–1.0	GIS	7, 8, 12, 18
covden_win	Vegetation cover density for winter (decimal percent)	0–0.723	GIS	7, 8, 12, 18
drnpar	Drainage factor for redistribution of saturate moisture storage to soil recharge as a function of hydraulic conductivity (inches/hour)	0.6	CAL	10
fastcoef_lin	Linear coefficient in downslope routing equation for preferential-flow storage (day^{-1})	0.0048–0.1061	COM	12
fastcoef_sq	Non-linear coefficient in downslope routing equation for preferential-flow storage	0.80	DEF	12
ground_melt	Daily rate of snowmelt at the snowpack-ground interface (millimeters per day)	0	DEF	8
gwflow_coef	Groundwater routing coefficient to obtain the groundwater flow contribution to streamflow (day^{-1})	0.01–0.05	CAL	13
gwsink_coef	Groundwater sink coefficient to compute the seepage from each reservoir to a groundwater sink (day^{-1})	0	DEF	13
gwstor_init	Storage in each groundwater reservoir at the beginning of the simulation (inches)	0.208–4.407	CAL	13
hru_deplcrv	Index number for snowpack depletion curve	1	DEF	8
hru_percent_imperv	Portion of HRU area that is impervious (decimal percent)	0–0.43	GIS	1, 8, 18
imperv_stor_max	Maximum impervious retention storage for the HRU (inches)	0.135–2.83	GIS	9, 10
jh_coef_hru	Air-temperature coefficient used in the Jensen and Haise (1963) potential-evapotranspiration computations for each HRU	16.2–18.7	COM	6
kpar	Hydraulic conductivity of the transmission zone (inches per hour)	1.53–5.00	CAL	10
melt_base	Base temperature used in calculation of snowmelt during periods of no rain (degree Celsius)	0	DEF	8

Table 3. Source of parameter values for selected model hydrologic response unit (HRU) distributed parameters for the Delaware River main-stem subbasin, Pennsylvania, New Jersey, and New York (modified from Jeton, 2000; Koczot and others, 2005).—Continued

[CAL, parameters that (a) cannot be estimated from available data and are adjusted during calibration or (b) have initial estimates from measured or published data that were adjusted during calibration; DEF, parameters that are considered constant, as provided by Leavesley and others (1983); LIT, obtained from the literature as estimated or empirical estimates (Black, 1996, table 4-1, p. 93); GIS, computed in geographic information system from digital coverages; COM, computed from climatological data or other measured data]

Model parameter	Description of model parameter	Range of values	Source of values	PRMS module ID[1]
mf_max	Annual maximum factor in snowmelt cycle (millimeters per degree Celsius per day)	0.50–7.94	CAL	8
mf_min	Annual minimum factor in snowmelt cycle (millimeters per degree Celsius per day)	0.13–3.99	CAL	8
negmf_max	Maximum negative snowmelt factor (millimeters per degree Celsius per day)	0.6	DEF	8
ofp_alpha	Kinematic routing parameter “a” for overland flow plane	0.003	DEF	11
ofp_cmp	Kinematic routing parameter “m” for overland flow plane	1.67	DEF	11
ofp_impv_alpha	Kinematic routing parameter “a” for impervious overland flow	2.0	DEF	11
ofp_impv_cmp	Kinematic routing parameter “m” for impervious overland flow	1.67	DEF	11
ofp_rough	Roughness parameter for overland flow plane	0.005	DEF	11
ofp_thresh	Minimum depth of flow to continue overland flow routing (inches)	0.00001	CAL	11
pref_flow_den	Preferential-flow pore density (decimal percent)	0–0.127	GIS	12
psp	Product of moisture deficit and capillary drive for soil recharge equal to field capacity (inches)	5.208–24.997	CAL	10
rad_trncf	Transmission coefficient for short-wave radiation through the winter canopy (decimal percent)	0.196–0.935	COM	8
rain_sub_adj	Monthly adjustment to rainfall by subbasin	0.6–3.0	CAL	4
rgf	Ratio of psp at field capacity to psp at wilting point	9.5	DEF	10
sat_threshold	Soil saturation threshold (inches)	3.00–8.86	COM	12
sat_threshold_adj	Adjustment factor for total soil saturation capacity	1.25	DEF	12
slowcoef_lin	Linear gravity-flow reservoir routing coefficient (day^{-1})	0.00031–0.00697	COM	12
slowcoef_sq	Non-linear gravity-flow reservoir routing coefficient	0.1	DEF	12
smidx_coef	Coefficient in the nonlinear contributing area algorithm computing surface runoff (decimal fraction)	0.0001–0.8473	CAL	9
smidx_exp	Exponent in nonlinear contributing area algorithm computing surface runoff ($inch^{-1}$)	0.205–0.787	CAL	9
snarea_thresh	Maximum snow water equivalent below which the snow-covered area depletion curve is applied (inches)	0.075–7.490	COM	8
snow_intcp	Snow interception storage capacity for the major vegetation type on an HRU (inches)	0.00047–0.06673	GIS	7
snow_sub_adj	Monthly adjustment to snowfall by subbasin	1.0–2.875	CAL	4

Table 3. Source of parameter values for selected model hydrologic response unit (HRU) distributed parameters for the Delaware River main-stem subbasin, Pennsylvania, New Jersey, and New York (modified from Jeton, 2000; Koczot and others, 2005).—Continued

[CAL, parameters that (a) cannot be estimated from available data and are adjusted during calibration or (b) have initial estimates from measured or published data that were adjusted during calibration; DEF, parameters that are considered constant, as provided by Leavesley and others (1983); LIT, obtained from the literature as estimated or empirical estimates (Black, 1996, table 4-1, p. 93); GIS, computed in geographic information system from digital coverages; COM, computed from climatological data or other measured data]

Model parameter	Description of model parameter	Range of values	Source of values	PRMS module ID[1]
snowinfil_max	Maximum infiltration rate for snowmelt (inches per day)	2.727–3.943	CAL	9
soil2gw_max	Amount of soil water excess for an HRU that is routed directly to the associated groundwater reservoir each day (inches)	0.00002–0.35233	CAL	12
soil_moist_adj	Adjustment factor for soil_moist_max parameter	1.0	DEF	12
soil_moist_init	Initial value of available water in soil profile (inches)	0.076–1.30	GIS	12
soil_moist_max	Maximum available water-holding capacity of soil profile (inches)	0.00024–19.993	CAL	9, 12
soil_rechr_init	Initial value for available water in the soil recharge zone (inches) (upper soil zone)	1.0	DEF	12
soil_rechr_max	Maximum value for available water in the soil recharge zone (inches)	0.00008–19.0275	CAL	12
soil_type	HRU soil type (sand, loam, or clay)	Sand or loam	GIS	12
srain_intcp	Summer interception storage capacity for the major vegetation type on an HRU (inches)	0.00073–0.05	GIS	7
ss2gw_rate	Coefficient to route water from subsurface reservoirs to groundwater reservoirs (day^{-1})	0.08521–0.12322	COM	12
ssrmax_coef	Coefficient to route water from subsurface reservoirs to groundwater reservoirs (inches)	1.0	DEF	12
ssstor_init	Initial storage in each subsurface reservoir (inches)	0	DEF	12
transp_beg	Month to begin summing maximum temperature for each HRU; when sum is greater than or equal to TRANSP_TMAX transpiration begins	April–May	LIT	6
transp_end	Month to stop transpiration	November	LIT	6
transp_tmax	Temperature index to determine the specific date of the start of the transpiration period (degrees)	0–1,000	COM	6
wind_adjust	Rate of snowmelt due to wind effects (millimeters per millibar per day)	0.0344–0.9956	CAL	8
wpcoef_a	Wetted perimeter coefficient “a”	0	DEF	14
wpcoef_b	Wetted perimeter coefficient “b”	0	DEF	14
wrain_intcp	Winter rain interception storage capacity for the major vegetation type on an HRU (inches)	0.0005–0.0357	GIS	7

[1]PRMS modules are listed on table 2.

Table 4. Selected whole-model nondistributed parameters estimated by calibration and ranges of values for the Delaware River main-stem subbasin, Pennsylvania, New Jersey, and New York (modified from Jeton, 2000; Koczot and others, 2005).

[DEF, parameters that are considered constant, as provided by Leavesley and others (1983); LIT, obtained from the literature as estimated or empirical estimates (Black, 1996, table 4-1, p. 93); CAL, parameters that (a) cannot be estimated from available data and are adjusted during calibration or (b) have initial estimates from measured or published data that were adjusted during calibration; ET, evapotranspiration; HRU, hydrologic response unit]

Model parameter	Description of model parameter	Range of values	Source of values	PRMS module ID[1]
albset_rna	Proportion of rain in a rain-snow event above which the snow albedo is not reset; snowpack accumulation stage (decimal percent)	0.8	DEF	8
albset_rnm	Proportion of rain in a rain-snow event above which the snow albedo is not reset; snowpack melt stage (decimal percent)	0.6	DEF	8
albset_sna	Minimum snowfall, in water equivalent, needed to reset snow albedo during the snowpack accumulation stage (inches)	0.05	DEF	8
albset_snm	Minimum snowfall, in water equivalent, needed to reset snow albedo during the snowpack melt stage (inches)	0.2	DEF	8
cecn_coef	Monthly convection condensation coefficient (calories per degree Celsius above 0 degrees Celsius)	5.0	DEF	8
chan_chi	Finite difference weighting factor for each channel segment (decimal percent)	0.6	DEF	14
chan_theta	Finite-difference spatial weighting factor for each channel segment (decimal percent)	0.5	DEF	14
dday_intcp	Monthly intercept in degree-day relation when estimating potential solar radiation (degree-days)	(-45)–(-6)	LIT	5
dday_slope	Monthly slope in degree-day relation when estimating potential solar radiation (degree-days per degree)	0.31–0.65	LIT	5
den_init	Initial density of new-fallen snow (grams per cubic centimeter)	0.1	DEF	8
den_max	Average maximum density of snowpack (grams per cubic centimeter)	0.6	DEF	8
emis_noppt	Average emissivity of air on days without precipitation	0.757	DEF	8
freeh2o_cap	Free-water holding capacity of snowpack	0.05	DEF	8
ground_melt	Daily rate of snow melt at the snowpack_ground interface (millimeters per day)	0	DEF	8
jh_coef	Monthly air-temperature coefficient used in the Jensen and Haise (1963) potential-evapotranspiration computations.	0.0038–0.0068	LIT	6
melt_base	Base temperature used in calculation of snowmelt during periods of no rain (degree Celsius)	0	DEF	8
melt_look	Julian date to start looking for spring snowmelt	30	CAL	8
melt_force	Julian date to force snowpack to spring snowmelt	60	CAL	8
mf_curve	Monthly snowmelt curve factor	0.5	DEF	8
ofp_chi	Finite difference weighting factor for overland flow routing	0.6	DEF	11
ofp_theta	Finite-difference spatial weighting factor for overland flow routing	0.5	DEF	11
potet_sublim	Proportion of potential ET sublimated from snow surface	0.75	CAL	7, 8
potet_sublim_st	Proportion of potential ET sublimated from snow surface in storm mode	0.75	DEF	8
ppt_rad_adj	Solar radiation reduced if precipitation exceeds this value (inches)	0.02	DEF	5
radadj_intcp	Intercept in temperature-solar radiation relation (degree-day)	1	DEF	5
radadj_slope	Slope in temperature-solar radiation relation (degree-day per degree)	0	DEF	5
radj_sppt	Adjustment factor for computed summer solar radiation when precipitation is greater than ppt_rad_adj	0.44	DEF	5
radj_wppt	Adjustment factor for computed winter solar radiation when precipitation is greater than ppt_rad_adj	0.5	DEF	5

Table 4. Selected whole-model nondistributed parameters estimated by calibration and ranges of values for the Delaware River main-stem subbasin, Pennsylvania, New Jersey, and New York (modified from Jeton, 2000; Koczot and others, 2005).—Continued

[DEF, parameters that are considered constant, as provided by Leavesley and others (1983); LIT, obtained from the literature as estimated or empirical estimates (Black, 1996, table 4-1, p. 93); CAL, parameters that (a) cannot be estimated from available data and are adjusted during calibration or (b) have initial estimates from measured or published data that were adjusted during calibration; ET, evapotranspiration; HRU, hydrologic response unit]

Model parameter	Description of model parameter	Range of values	Source of values	PRMS module ID[1]
radmax	Maximum portion of potential solar radiation that reaches ground after atmospheric interferences (haze, dust, smog, etc.) (decimal percent)	0.8	DEF	5
rain_min	Minimum rainfall rate triggering rain-on-snow melt estimates (millimeters per hour)	0.25	DEF	8
settle_constant	Snowpack settlement time constant	0.1	DEF	8
snarea_curve	Snow area depletion curves values	0.05–1.0	CAL	8
sntemp_thresh	Threshold snowfall rate above which the temperature index of snowpack is reset to temperature of new snowfall (millimeters per hour)	1.5	DEF	8
tmax_allrain	Precipitation all rain if maximum HRU temperature is equal to or greater than this monthly value (degrees)	44	CAL	5
tmax_allsnow	Precipitation all snow if maximum HRU temperature is equal to or less than this value (degrees)	32	DEF	8
tmax_index	Index temperature used to determine precipitation adjustments to solar radiation (degrees)	30–70	CAL	5
tstorm_mo	Months when convective storms are prevalent	May–Sept	LIT	8

[1]PRMS modules are listed on table 2.

The PRMS parameter hru_percent_imperv, the HRU impervious surface as a decimal percent of the total HRU area, is determined using GIS processing of the land cover and impervious area data sets. The land cover and impervious surface for the study area are shown in figures 3 and 4, and the resultant hru_percent_imperv values assigned to each HRU are shown in figure 5. The HRU value of the parameter is the average percent impervious for each of the land-cover rasters that fall within the HRU polygon, scaled by a factor to account for isolated impervious areas that drain to pervious areas, and do not directly contribute to rapid runoff. The scale factor yields an effective impervious surface area that is less than the actual area, with a smaller reduction for “urban” HRUs where the actual impervious area is larger than 10 percent. The scale factor formulae were determined by analysis of storm runoff in Connecticut by Bjerklie and others (D.M. Bjerklie, U.S. Geological Survey, written commun., 2008) and from previous studies (Alley and Veenhuis, 1983; Sutherland, 1995, 2005). The land-cover data set was used for verification, adjusting impervious area where the land cover is not developed, and was used for estimation of other parameters, such as those controlling evapotranspiration. Similar procedures were used for determining initial values of other model parameters from raster data sets.

The PRMS model includes storm-mode simulation and, hence, includes cascading of runoff from HRU to HRU, eventually to stream segments and lakes, and flow routing in stream segments. Markstrom and others (2008, p. 33-34) describe the model parameters controlling cascading, which were identified through calibration for this study.

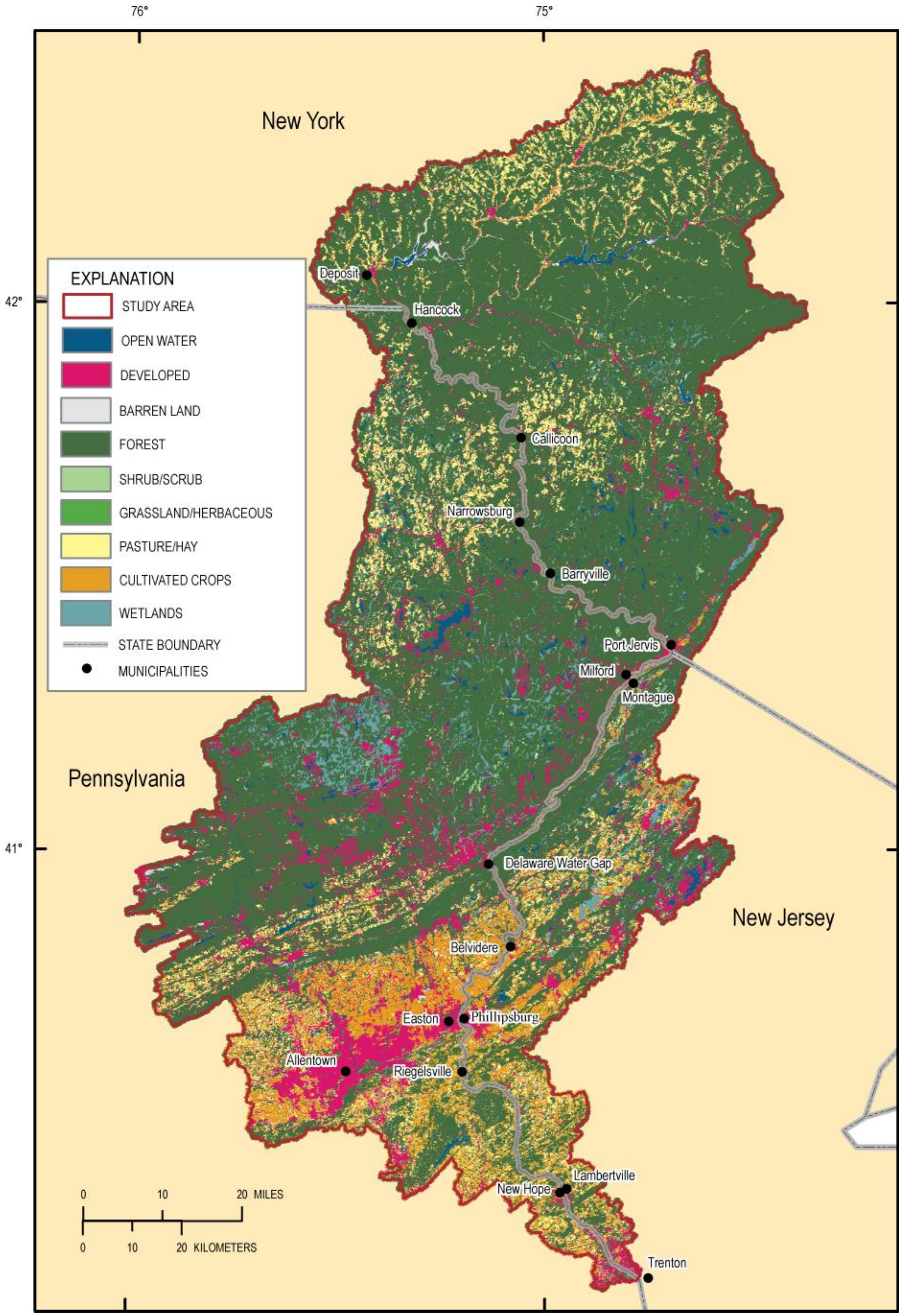

Figure 3. Land-cover data for the Delaware River main-stem subbasin, Pennsylvania, New Jersey, and New York, 2001 (data from Multi-Resolution Land Characteristics Consortium, 2001).

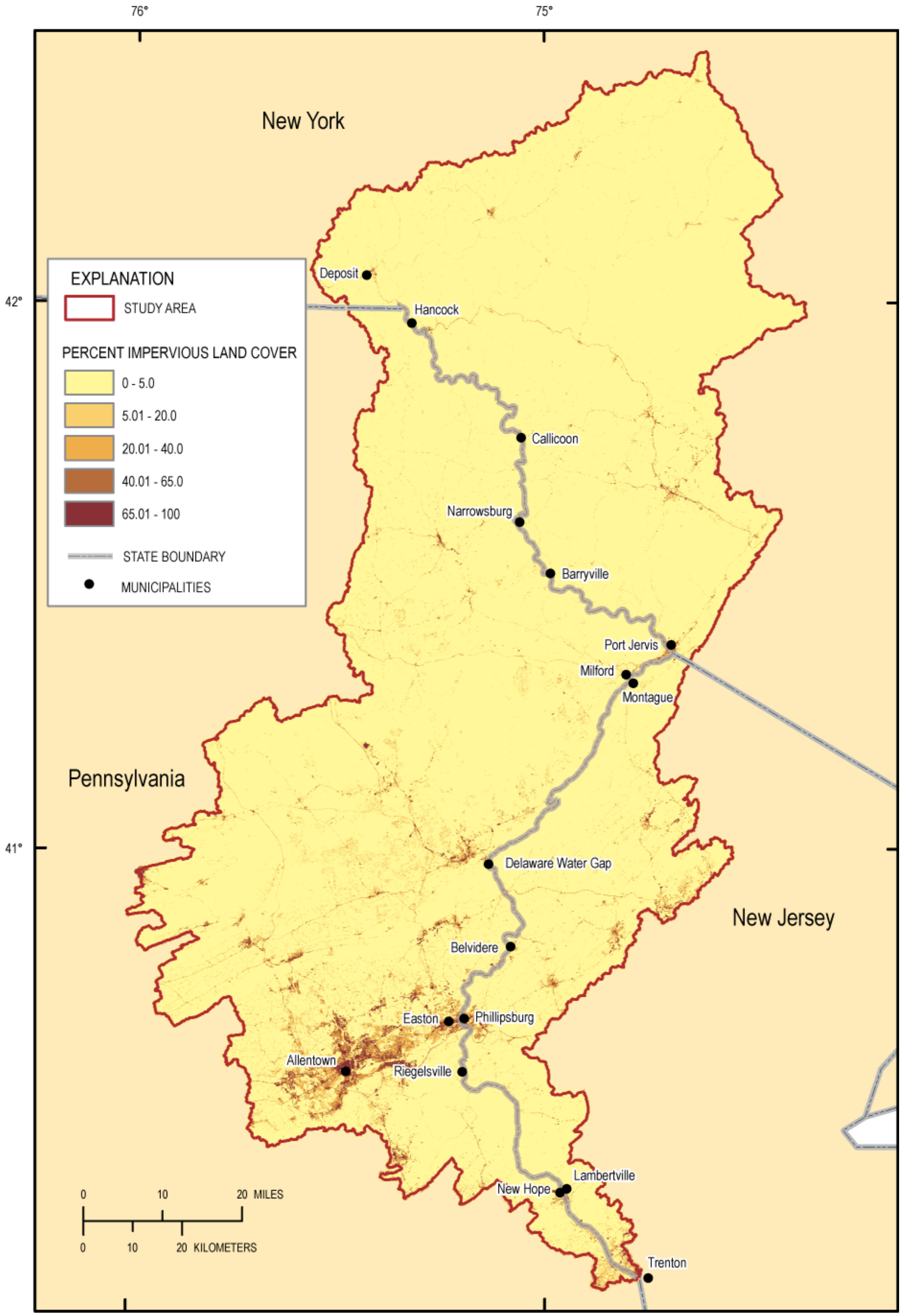

Figure 4. Impervious-surface data for the Delaware River main-stem subbasin, Pennsylvania, New Jersey, and New York, 2001 (data from Multi-Resolution Land Characteristics Consortium, 2001).

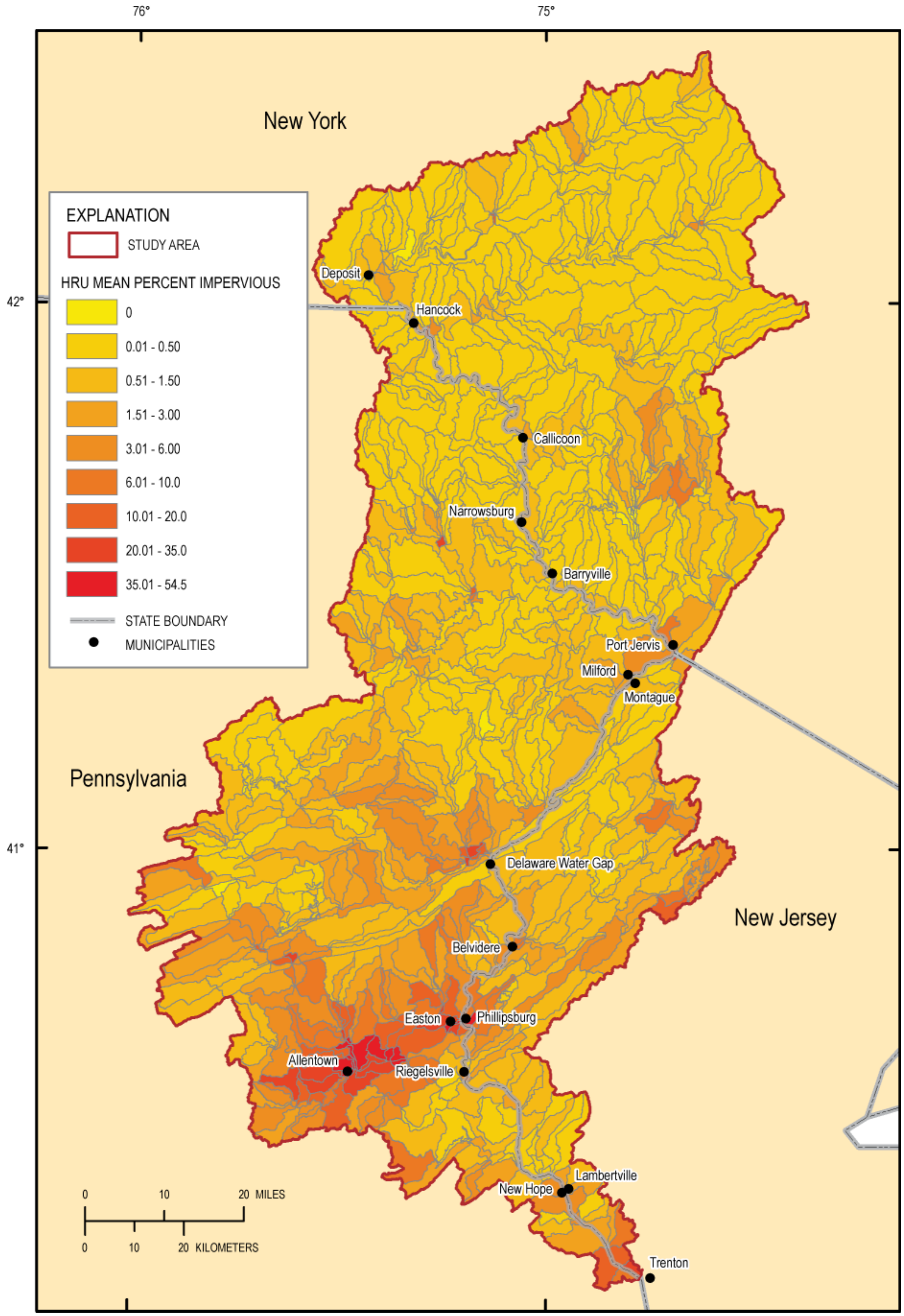

Figure 5. Mean percent impervious values for model hydrologic response units (HRUs) for the Delaware River main-stem subbasin, Pennsylvania, New Jersey, and New York.

Climate Data

Climate time-series data – precipitation, air temperature, and solar radiation – are primary input data for PRMS. PRMS operates in two modes, daily and storm, using climate time-series data with time steps of 1 day and 1 hour, respectively. The model operates using a daily time step (daily mode) for periods before and after the storm events and switching to an hourly time step during storm periods (storm mode). Daily-mode data consisted of total daily precipitation, minimum daily air temperature, maximum daily air temperature, and total daily solar radiation. Storm-mode data consisted of total hourly precipitation and total hourly solar radiation. Units of measurement used in the model are inches for precipitation, degrees Fahrenheit for temperature, and Langleys for solar radiation.

Climate Station Data

Climate data for point stations were obtained from multiple sources. These sources included daily data for 22 NWS Cooperative Climate Station (COOP) network stations, hourly data for 15 stations from the National Climatic Data Center (NCDC), hourly data for 1 station from MARFC records, and daily and hourly data for 7 stations operated by the New York City Department of Environmental Protection (NYCDEP) (fig. 6, table 5). Daily data were retrieved for the period January 1980 through December 2007. Not all data covered the complete period. Hourly data were retrieved for three storm periods: September 13, 2004, through September 27, 2004; March 24, 2005, through April 14, 2005; and June 19, 2006, through July 9, 2006. Because the availability of hourly climate data is limited both in areal coverage and location, not all hourly data were collocated with daily data stations and six daily stations had no corresponding hourly stations. Thirteen hourly stations were at varying distances from their associated daily station.

Daily precipitation and temperature data originated from the COOP network and NYCDEP meteorological stations. The COOP data were retrieved with Downsizer (Ward-Garrison & others, 2009; U.S. Geological Survey, 2008a), an automated program that performs quality-assurance/quality-control (QA/QC) checks and formats the data suitable for input directly to PRMS. The NYCDEP daily data were limited to at most the period 1994 through 2006. Automated and manual QA/QC were performed by NYCDEP up to the end of calendar year 2005. Data for 2006 did not undergo an agency QA/QC check and should be considered provisional (Glenn Horton, New York City Department of Environmental Protection, written commun., 2007).

Hourly precipitation and temperature data originated from NCDC quality-controlled local climate data (National Climatic Data Center, 2007) and NYCDEP meteorological stations. No additional QA/QC was performed on NCDC hourly data. Additional QA/QC for NYCDEP hourly data consisted of completion of missing time-series entries, parsing for missing or phantom precipitation by comparison to adjacent stations, and visual comparison with radar traces plotted against station locations in a GIS environment using the Java NEXRAD viewer (National Climatic Data Center, 2008).

Table 5. Selected climate stations in the Delaware River main-stem subbasin, Pennsylvania, New Jersey, and New York.

[COOP, National Weather Service Cooperative Climate Network; DP, Daily precipitation; DT, Daily temperature; NYCDEP, New York City Department of Environmental Protection; HP, Hourly precipitation; HT, Hourly temperature; MARFC, Middle Atlantic River Forecast Center; NCDC, National Climate Data Center]

Station name	State	Source	Source designation	Station altitude (feet)	Type
Flemington 5 NNW	N.J.	COOP	283029	260	DP, DT
Hightstown 2 W	N.J.	COOP	283951	100	DP, DT
Little Falls	N.J.	COOP	284887	150	DP, DT
Moorestown	N.J.	COOP	285728	45	DP, DT
Sussex 2 NE	N.J.	COOP	288644	649	DP, DT
Binghamton WSO Airport	N.Y.	COOP	300687	1,600	DP, DT
Delhi 2 SE	N.Y.	COOP	302036	1,440	DP, DT
Deposit	N.Y.	COOP	302060	1,000	DP, DT
Lansing Manor	N.Y.	COOP	304575	1,100	DP, DT
Liberty 1 NE	N.Y.	COOP	304731	1,549	DP, DT
Slide Mountain	N.Y.	COOP	307799	2,650	DP, DT
Walden 1 ESE	N.Y.	COOP	308906	380	DP, DT
Walton 2	N.Y.	COOP	308932	1,480	DP, DT
Allentown AP	Pa.	COOP	360106	390	DP, DT
Blue Marsh Lake	Pa.	COOP	360785	350	DP, DT
Graterford 1 E	Pa.	COOP	363437	240	DP, DT
Neshaminy Falls	Pa.	COOP	366194	60	DP, DT
Palm 3 SE	Pa.	COOP	366681	300	DP, DT
Pleasant Mount 1 W	Pa.	COOP	367029	1,799	DP, DT
Reading 4 NNW	Pa.	COOP	367322	360	DP, DT
Tobyhanna Pocono Mountain A	Pa.	COOP	368893	1,916	DP, DT
Wilkes Barre WSO Airport	Pa.	COOP	369705	930	DP, DT
Cannonsville Dam near Stilesville	N.Y.	NYCDEP	DCM074	1,169	DP, DT, HP, HT
Tymeson Farm on Dunk Hill Road near Walton	N.Y.	NYCDEP	DCM076	2,091	DP, DT, HP, HT
Eklund Farm on Bruce Hill Road near Stamford	N.Y.	NYCDEP	DCM077	2,242	DP, DT, HP, HT
Big Bend Club on Hunter Road near Claryville	N.Y.	NYCDEP	DNM147	2,200	DP, DT, HP, HT
Pepacton Dam near Downsville	N.Y.	NYCDEP	DPM110	1,200	DP, DT, HP, HT
Hillriegel Farm on Millbrook near Margaretville	N.Y.	NYCDEP	DPM111	2,199	DP, DT, HP, HT
Triple View Farm on Sally's Alley near Vega	N.Y.	NYCDEP	DPM112	2,248	DP, DT, HP, HT
Pleasant Mount GOES	Pa.	MARFC	PLXP1	1,810	HP
Somerset County Airport	N.J.	NCDC	SMQ	100	HP, HT
Trenton-Mercer County Airport	N.J.	NCDC	TTN	213	HP, HT
Caldwell-Essex County Airport	N.J.	NCDC	CDW	174	HP, HT
South Jersey Regional Airport	N.J.	NCDC	VAY	53	HP, HT
Sussex County Airport	N.J.	NCDC	FWN	421	HP, HT
Binghamton Link Field Airport	N.Y.	NCDC	BGM	1,637	HP, HT
Monticello-Sullivan County Airport	N.Y.	NCDC	MSV	1,403	HP, HT
Montgomery-Orange County Airport	N.J.	NCDC	MGJ	365	HP, HT
Allentown-Bethlehem Airport	Pa.	NCDC	ABE	384	HP, HT

Table 5. Selected climate stations in the Delaware River main-stem subbasin, Pennsylvania, New Jersey, and New York.—Continued

[COOP, National Weather Service Cooperative Climate Network; DP, Daily precipitation; DT, Daily temperature; NYCDEP, New York City Department of Environmental Protection; HP, Hourly precipitation; HT, Hourly temperature; MARFC, Middle Atlantic River Forecast Center; NCDC, National Climate Data Center]

Station name	State	Source	Source designation	Station altitude (feet)	Type
Pottstown-Limerick Airport	Pa.	NCDC	PTW	309	HP, HT
Northeast Philadelphia Airport	Pa.	NCDC	PNE	119	HP, HT
Doylestown Airport	Pa.	NCDC	DYL	385	HP, HT
Reading-Spatz Field	Pa.	NCDC	RDG	353	HP, HT
Mount Pocono Airport	Pa.	NCDC	MPO	1,894	HP, HT
Wilkes Barre Airport	Pa.	NCDC	AVP	962	HP, HT

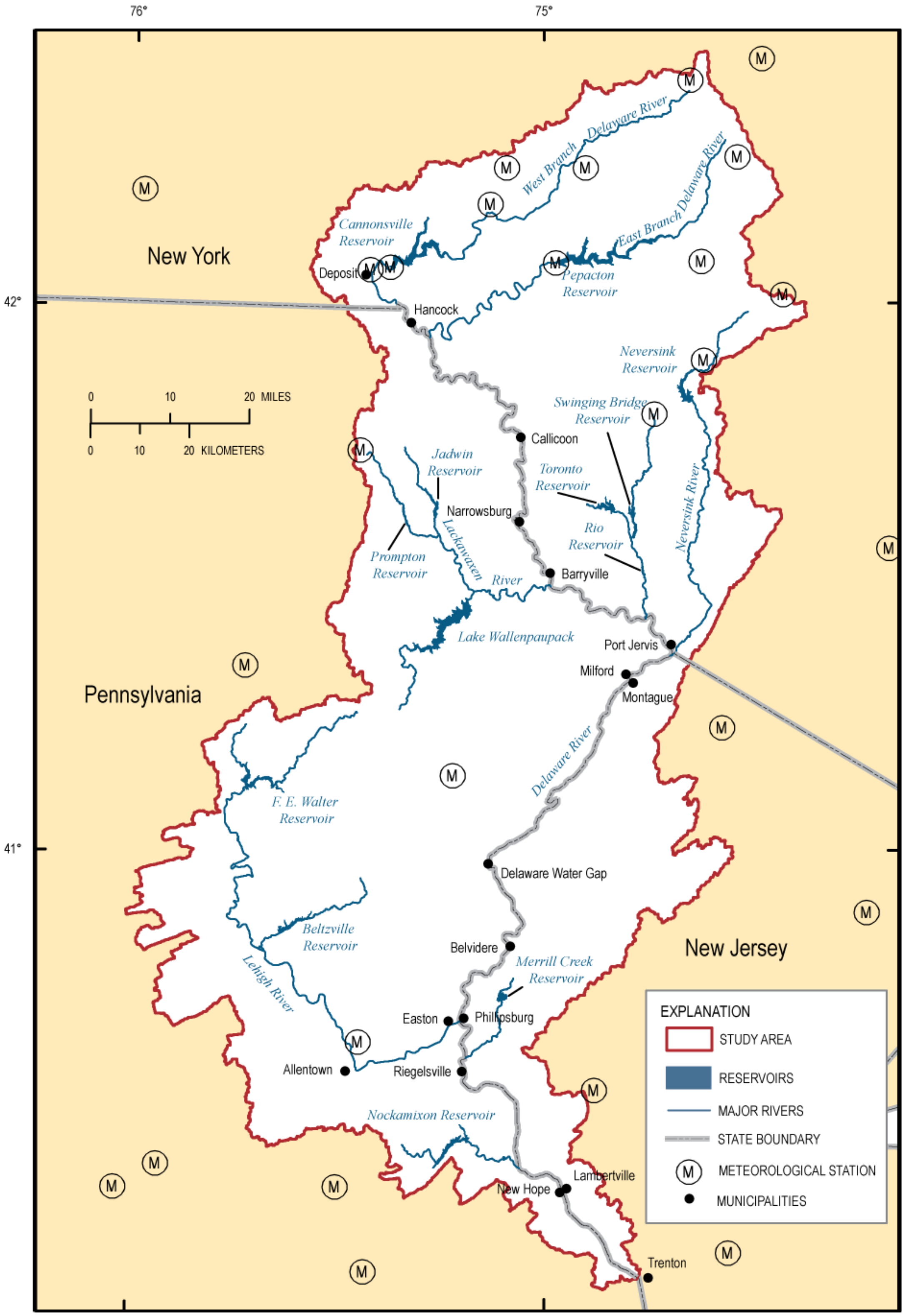

Figure 6. Locations of selected National Oceanic and Atmospheric Administration meteorological stations in the Delaware River main-stem subbasin, Pennsylvania, New Jersey, and New York.

Table 6. Solar-radiation stations used for model data for the Delaware River main-stem subbasin, Pennsylvania, New Jersey, and New York.

[NSRDB, National Renewable Energy Laboratory National Solar Radiation Database; NRCC, Northeast Regional Climate Center; NYCDEP, New York City Department of Environmental Protection]

Station name	State	Source[1]	Source designation	Station altitude (feet)
Philadelphia International Airport	Pa.	NSRDB; NRCC	724080; KPHL	28
Belmar-Farmingdale Airport	N.J.	NSRDB; NRCC	724084; BLM	159
Northeast Philadelphia Airport	Pa.	NSRDB; NRCC	724085; PNE	119
Willow Grove Naval Air Station	Pa.	NSRDB	724086	362
Caldwell-Essex County Airport	N.J.	NSRDB; NRCC	724094; CDW	174
Trenton-Mercer County Airport	N.J.	NSRDB; NRCC	724095; TTN	213
McGuire Air Force Base	N.J.	NSRDB; NRCC	724096; WRI	133
Montgomery-Orange County Airport	N.J.	NSRDB; NRCC	725015; MGJ	365
Doylestown Airport	Pa.	NSRDB; NRCC	725113; DYL	385
Wilkes Barre Airport	Pa.	NSRDB; NRCC	725130; AVP	962
Monticello-Sullivan County Airport	N.Y.	NSRDB; NRCC	725145; MSV	1,403
Binghamton Link Field Airport	N.Y.	NSRDB; NRCC	725150; BGM	1,637
Allentown-Bethlehem Airport	Pa.	NSRDB; NRCC	725170; ABE	384
Albany County Airport	N.Y.	NSRDB	725180	292
Mount Pocono Airport	Pa.	NSRDB; NRCC	725434; MPO	1,916
Cannonsville Dam near Stilesville	N.Y.	NYCDEP	DCM074	1,169
Tymeson Farm on Dunk Hill Road near Walton	N.Y.	NYCDEP	DCM076	2,091
Eklund Farm on Bruce Hill Road near Stamford	N.Y.	NYCDEP	DCM077	2,242
Big Bend Club on Hunter Road near Claryville	N.Y.	NYCDEP	DNM147	2,200
Pepacton Dam near Downsville	N.Y.	NYCDEP	DPM110	1,200
Hillriegel Farm on Millbrook near Margaretville	N.Y.	NYCDEP	DPM111	2,199
Triple View Farm on Sally's Alley near Vega	N.Y.	NYCDEP	DPM112	2,248

[1] Data transitions from NSRDB to NRCC on 1/1/2006.

Solar-radiation data for 15 airports and 7 NYCDEP locations (table 6) were obtained from the National Renewable Energy Laboratory National Solar Radiation Database (NSRDB), the Northeast Regional Climate Center (NRCC), and the NYCDEP. Data for 1980 through 2005 consisted of hourly METSTAT modeled and measured values of global horizontal radiation published by the NSRDB for the airport locations (National Renewable Energy Laboratory, 1992, 2007). Daily solar-radiation data for this period were generated by aggregation of hourly data. For 2006 through 2007, solar-radiation data at 13 airport sites consisted of hourly and daily estimates of total (global) horizontal radiation produced by the NRCC on the basis of a modified Meyers and Dale model (DeGaetano and others, 1993). If data were not available for an hour, available data from a nearby location were substituted. A considerable amount of data was missing for Monticello (MSV). Nearby Stewart Field was the backup station, and its data were used extensively in the Monticello files (Keith Eggleston, Northeast Regional Climate Center, written commun., 2008). No additional QA/QC was performed on NSRDB and NRCC solar-radiation data. The NYCDEP hourly solar-radiation data consisted of measured values collected at seven locations and covered 1994 through 2006. QA/QC for NYCDEP hourly solar-radiation data consisted of parsing for gross radiation errors on the basis of adjacent stations, time of observation errors, duplicate values, and non-zero values during night periods. NYCDEP solar data consisted of hourly data aggregated to total daily.

Review of the temperature and precipitation data quality and initial model-calibration efforts indicated that these hourly station data could not be used in the model-calibration procedures. In particular, available calibration tools for the model were not compatible with different locations for daily and hourly gages. New procedures were developed to estimate the hourly temperature from daily minimum and maximum temperature and to estimate hourly and daily precipitation from NWS hourly radar data.

Estimation of Hourly Temperature Using Daily Station Data

New procedures were developed to estimate the hourly temperature from daily minimum and maximum temperature. Daily maximum and minimum temperature were produced for each HRU using PRMS in daily mode, and the *xyz* distribution technique documented by Hay and others (2000), Hay and Clark (2003), and Hay and others (2002). The daily values were used with a modeled hourly temperature variation to produce hourly values of temperature for each HRU.

The method of Erbs and others (1983) was used to estimate the hourly temperature at daily station locations from daily minimum and maximum values. This method was compared against other air-temperature models by Bilbao and others (2002) and shown to perform well and can be adapted to work at daily timescale. For each simulation day in storm mode, the hourly temperature for a HRU, T(*ihr*), was computed from the daily maximum temperature (tmax) and minimum temperature (tmin) for the HRU:

$$T(ihr) = tavg + (A * (0.4632 * \cos(x - 3.805) + 0.0984 * \cos(2x - 0.360) + 0.0168 * \cos(3x - 0.822) + 0.0138 * \cos(4x - 3.513))) \quad (1)$$

where $tavg = (tmax-tmin)/2$
$A = (tmax-tmin)$
$x = (2.0*3.14159265) * (ihr-1)/24$
ihr = index of hour of the day, from 1 to 24

Precipitation Estimated from Radar Data

The NWS Multisensor Precipitation Estimate (MPE) data set was used for precipitation input during daily and storm simulations with PRMS and was provided for this study by NOAA's NWS MARFC (Joseph Ostrowski, NWS Middle Atlantic River Forecast Center, written commun., 2008). The MPE is a 4-km resolution gridded data set that is based on NEXRAD radar precipitation measurements. The original NEXRAD values are adjusted by NWS to improve the accuracy and reduce bias using land-based gage measurements. National Weather Service, Hydrology Laboratory (2009) provides background information and technical details on the MPE data sets. The hourly totals MPE data set used for this study covers the Delaware River Basin for 2001-2007. An example of the MPE data for 9 a.m. Eastern Standard Time (EST) on September 18, 2004, is shown in figure 7.

The MPE data sets were preprocessed to reduce computations during PRMS simulations. The MPE was provided as a XMRG formatted data set of hourly totals. This was converted to two text file format data sets for subsequent simulation: (1) a data set of hourly precipitation by HRU, and (2) a data set of daily precipitation by HRU. These text files are much smaller than the original gridded data set, have times converted from GMT to EST, and incorporate mapping of the MPE grid values to the HRUs using a simple area-weighted average. For example, figure 8 shows the model precipitation by HRU for 9 a.m. EST on September 18, 2004. Hourly totals were summed for the daily data set.

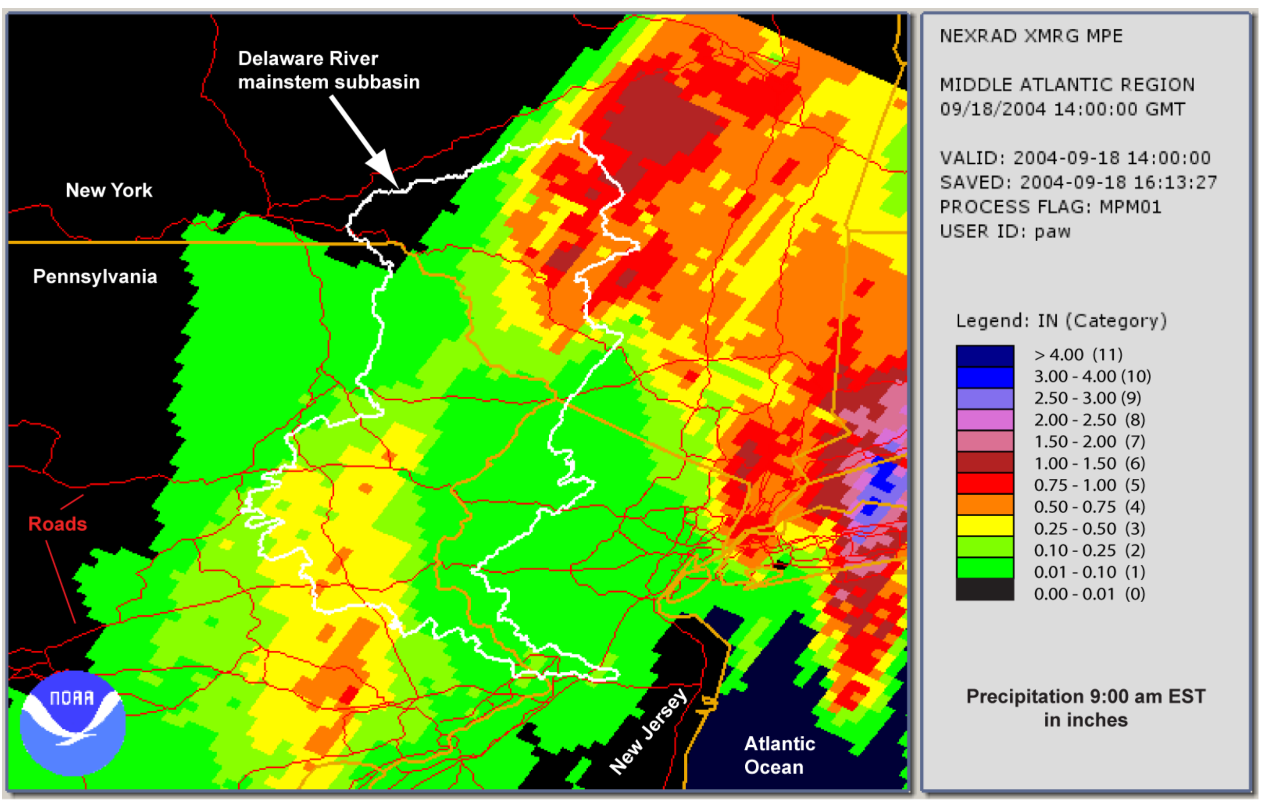

Figure 7. National Weather Service Multi-sensor Precipitation Estimate (MPE) hourly data for 9 a.m. Eastern Standard Time on September 18, 2004, used for model data for the Delaware River main-stem subbasin, Pennsylvania, New Jersey, and New York.

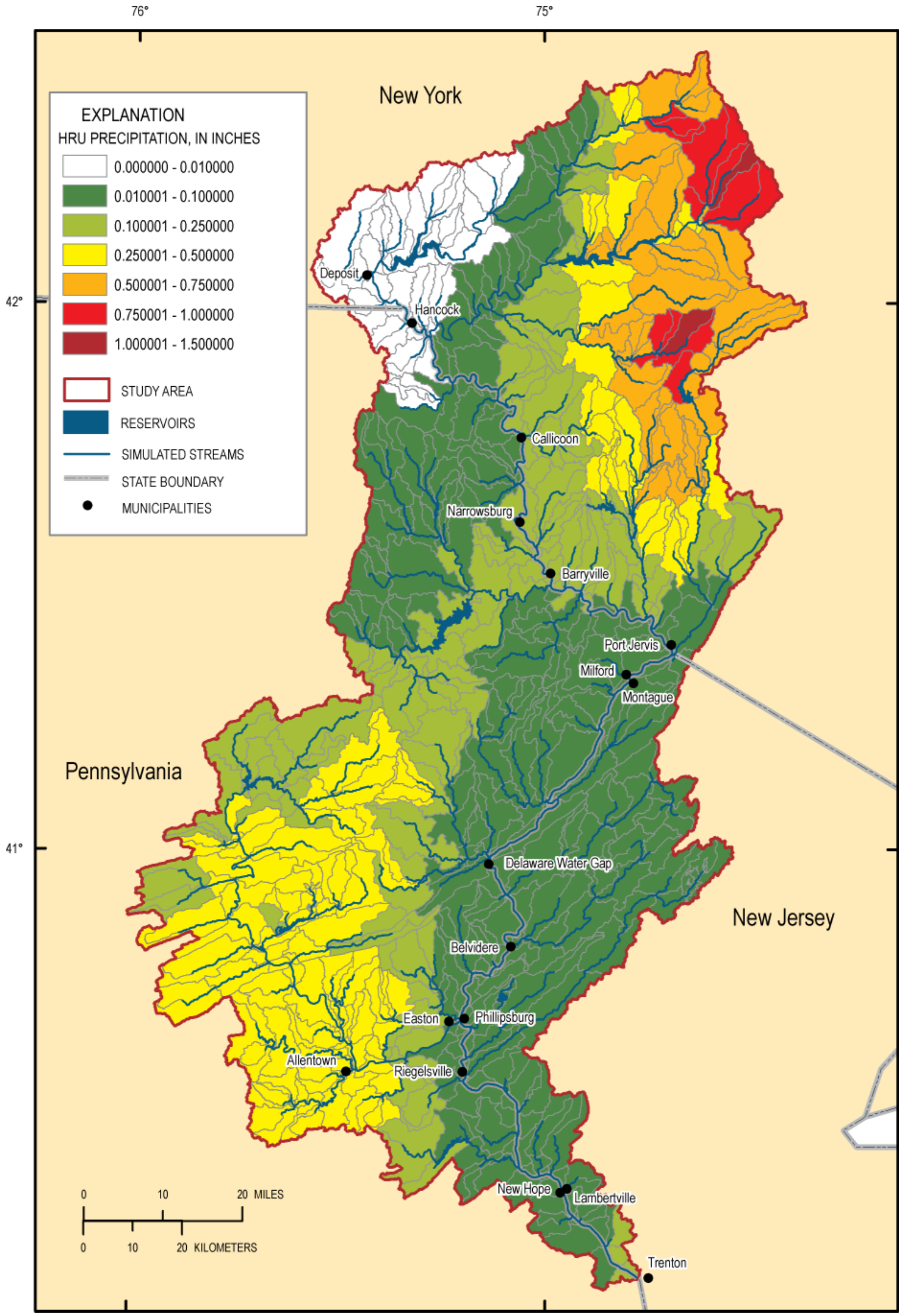

Figure 8. Model hourly precipitation for 9 a.m. Eastern Standard Time on September 18, 2004, for Hydrologic Response Units (HRUs) for the Delaware River main-stem subbasin, Pennsylvania, New Jersey, and New York.

Model Application

Calibration and Testing

Calibration of PRMS included regression and optimization algorithms, as well as manual adjustments. The general goal of the calibration procedure was to minimize the difference between streamflow (discharge) measured at USGS streamgages and the corresponding discharge simulated by PRMS.

The normalized root mean square error *(NRMSE)* is an objective function that measures the overall difference between the simulated and observed streamflows. For the daily values, $NRMSE_d$ is defined as

$$NRMSE_d = \left(\sum_{n=1}^{ndays} \left(MSD_n - SIM_n \right)^2 \Big/ \sum_{n=1}^{ndays} \left(MSD_n - MN \right)^2 \right)^{1/2} \qquad (2)$$

where *n* is the day index; *ndays* is the total number of days; and *MSD*, *SIM*, and *MN* are the observed, simulated, and mean observed daily flow. The mean observed daily flow, *MN*, is computed for the days of the simulation period only. If *NRMSE* = 0, then the simulated flows are identical to the observed flows. A value of *NRMSE* = 1 indicates that the sum of squared differences between the observed and simulated flows is the same as the sum of squared differences between the observed flows and the mean observed flow.

For the hourly values, $NRMSE_h$ is defined as

$$NRMSE_h = \left(\sum_{m=1}^{nhours} \left(MSH_m - SIMH_m \right)^2 \Big/ \sum_{m=1}^{nhours} \left(MSH_m - MNH \right)^2 \right)^{1/2} \qquad (3)$$

where *m* is the hour index; *nhours* is the total number of hours; and *MSH*, *SIMH*, and *MNH* are the observed, simulated, and mean observed hourly flow. The mean observed hourly flow, *MNH*, is computed for the hours of the storm-mode simulation only.

Daily and hourly streamflow data from 42 USGS streamgages (table 7 and fig. 9) were acquired for use in model calibration. Simulated streamflow was compared to data from 35 streamgages at corresponding locations, and streamflow data from the other 7 streamgages were used as reservoir discharge for calibration at downstream locations. The streamflow data represent areas draining from 20.2 to 6,780 mi^2. Streamflow data were collected by the USGS using techniques described by Rantz and others (1982). Continuous streamflow data were retrieved from the National Water Information System (NWIS) (Hoopes, 2004; Sauer, 2002). The hourly calibration simulations included three time periods before, during, and after high-flow events: September 13 to 27, 2004; March 24 to April 14, 2005; and June 19 to July 9, 2006.

Table 7. Streamgages selected for use in model calibration for the Delaware River main-stem subbasin, Pennsylvania, New Jersey, and New York.

[Use codes: C, calibration; R, reservoir discharge; $NRMSE_d$ and $NRMSE_h$, normalized root mean square error, daily and hourly respectively]

U.S. Geological Survey station number	Station name	Drainage area (square miles)	Use	Model daily fit statistic $NRMSE_d$	Model hourly fit statistic $NRMSE_h$
01413500	East Branch Delaware River at Margaretville, N.Y.	163	C	1.26	0.43
01414000	Platte Kill at Dunraven, N.Y.	34.9	C	.83	.45
01414500	Mill Brook near Dunraven, N.Y.	25.2	C	.98	.70
01415000	Tremper Kill near Andes, N.Y.	33.2	C	1.03	.60
01417000	East Branch Delaware River at Downsville, N.Y.	372	R		
01417500	East Branch Delaware River at Harvard, N.Y.	458	C	.16	.32
01420500	Beaver Kill at Cooks Falls, N.Y.	241	C	1.01	.45
01421000	East Branch Delaware River at Fishs Eddy, N.Y.[1]	784	C	.54	.25
01423000	West Branch Delaware River at Walton, N.Y.	332	C	.60	.25
0142400103	Trout Creek near Trout Creek, N.Y.	20.2	C	.67	.49
01425000	West Branch Delaware River at Stilesville, N.Y.	456	R		
01426000	Oquaga Creek at Deposit, N.Y.	67.6	C	.74	.45
01426500	West Branch Delaware River at Hale Eddy, N.Y.	595	C	.19	.21
01427510	Delaware River at Callicoon, N.Y.	1,820	C	.45	.20
01428500	Delaware River above Lackawaxen River near Barryville, N.Y.	2,020	C	.50	.23
01428750	West Branch Lackawaxen River near Aldenville, Pa.	40.6	C	.87	.46
01429000	West Branch Lackawaxen River at Prompton, Pa.	59.7	R		
01429500	Dyberry Creek near Honesdale, Pa.	64.6	R		
01431500	Lackawaxen River at Hawley, Pa.	290	C	.60	.37
01432900	Mongaup River at Mongaup Valley, N.Y.	76.6	C	.74	.28
01434000	Delaware River at Port Jervis, N.Y.	3,070	C	.64	.22
01435000	Neversink River near Claryville, N.Y.	66.6	C	1.39	.57
01436000	Neversink River at Neversink, N.Y.	92.6	R		
01436690	Neversink River at Bridgeville, N.Y.	171	C	.52	.42
01437500	Neversink River at Godeffroy, N.Y.	307	C	.59	.39
01438500	Delaware River at Montague, N.J.	3,480	C	.64	.23
01439500	Bush Kill at Shoemakers, Pa.	117	C	.78	.36
01440000	Flat Brook near Flatbrookville, N.J.	64	C	.55	.42
01442500	Brodhead Creek at Minisink Hills, Pa.	259	C	.83	.35
01443500	Paulins Kill at Blairstown, N.J.	126	C	.72	.45
01446500	Delaware River at Belvidere, N.J.	4,535	C	.72	.21
01447500	Lehigh River at Stoddartsville, Pa.	91.7	C	.67	.33
01447720	Tobyhanna Creek near Blakeslee, Pa.	118	C	.56	.26
01447800	Lehigh River below Francis E Walter Res near White Haven, Pa.	290	R		
01449000	Lehigh River at Lehighton, Pa.	591	C	.34	.48
01449360	Pohopoco Creek at Kresgeville, Pa.	49.9	C	.50	.26
01449800	Pohopoco Creek below Beltzville Dam near Parryville, Pa.	96.4	R		
01450500	Aquashicola Creek at Palmerton, Pa.	76.7	C	.86	.45
01451000	Lehigh River at Walnutport, Pa.	889	C	.40	.34
01452000	Jordan Creek at Allentown, Pa.	75.8	C	.54	.47
01453000	Lehigh River at Bethlehem, Pa.	1,279	C	0.49	.27
01463500	Delaware River at Trenton, N.J.	6,780	C	0.79	.27

[1] Includes record from discontinued gage 01420980.

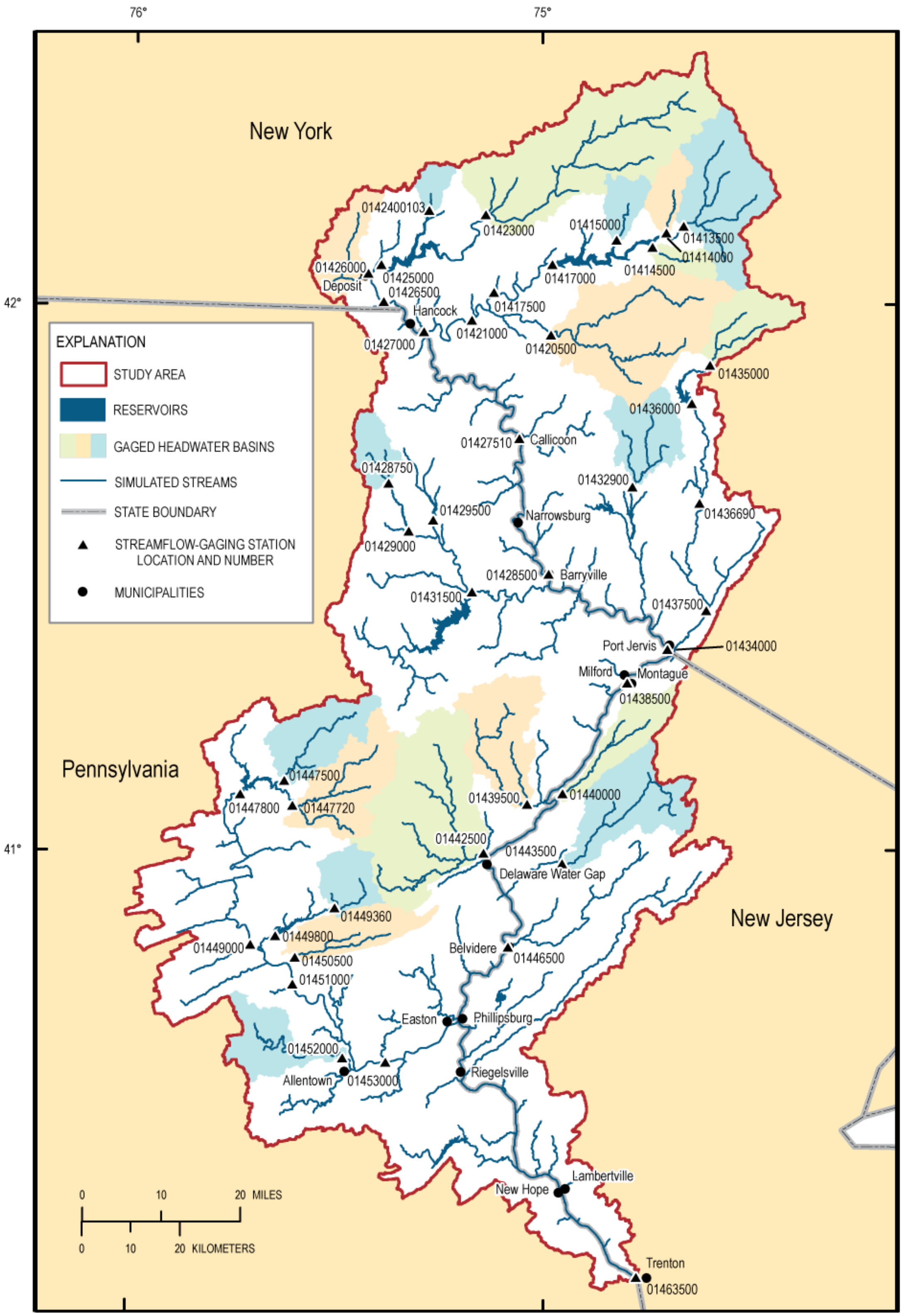

Figure 9. Location of selected streamgages in the Delaware River main-stem subbasin, Pennsylvania, New Jersey, and New York. (Streamgages are listed in table 7.)

Automatic calibration methods were used for the PRMS model, first in daily mode, and then in storm mode. The automatic calibration is performed using LUCA (Hay and Umemoto, 2007; Hay and others, 2006), an automatic calibration tool that adjusts model parameters to reduce the difference between simulated and measured daily streamflow. LUCA is based on the Shuffled Complex Evolution (Duan and others, 1993) global search algorithm that assures that intermediate and final states of the model are simulated consistently with measured values (Hay and Umemoto, 2007). Subbasins of the model were delineated above USGS streamgages, and the parameters of HRUs above each station are adjusted separately during LUCA calibration.

Headwater subbasins of the model were calibrated first (fig. 9). Calibration of model parameters for subbasins below the headwaters could then be calibrated, using the headwater flows from those calibrated subbasins. Thus, the calibration procedure started in the headwaters and then moved down through the watershed. Parameters for ungaged subbasins were assigned using values from the closest gaged subbasin.

Because the PRMS model is designed to provide runoff and inflows for a HEC-ResSim flood-analysis reservoir-simulation model, the reservoirs simulated in that model are not explicitly included in the PRMS model. This required a modified procedure for calibration of PRMS local inflows downstream of the reservoirs. For daily calibration of these downstream subbasins, the measured daily outflow from the reservoir was used as an inflow to the subbasin. In this way, the measured streamflow further downstream could be used as a calibration target for local flows below the reservoir in the PRMS model. Calibration changed the parameters controlling local inflows downstream of the reservoir, but the discharge from the reservoir was not adjusted. For the hourly calibration, additional manual calibration was conducted by using the HEC-ResSim model to simulate flow through the reservoirs, and to compute streamflow downstream of the reservoirs. Thus, the daily calibration uses only PRMS results and observed reservoir outflows, while hourly calibration results use both PRMS and HEC-ResSim for simulation of flows at streamgage locations below the reservoirs. Streamflow at headwater streamgages, which is not regulated by the reservoirs, is fully simulated by PRMS alone, for both daily and hourly simulations.

The PRMS model was calibrated in a three-step process: automatic calibration in daily mode, automatic calibration in storm mode, and manual calibration of storm volumes for main-stem gage locations. The first step was calibration of the parameters shown in table 8 using the model in daily mode. Two objective functions were used for the daily mode calibration, the absolute difference between the observed and simulated total volume of discharge, and the $NRMSE_d$ of the daily flows. The first objective function was used to determine precipitation adjustment factors, separately for rain and snow, by month, so that the total volume of water applied to the basin as precipitation is consistent with the total discharge measured at the subbasin streamgage.

The second objective function for the daily-mode calibration is a measure of the overall match between the simulated and observed daily hydrograph. Parameters adjusted on the basis of this measure of model fit are generally related to the partitioning of water between relatively slow and fast subsurface runoff reservoirs. The groundwater reservoir has a more delayed release of water than the soil-moisture reservoir. Daily calibration is chosen for these parameters because the timescale of release from both subsurface reservoirs is on the order of days, not hours. A single adjustment of each parameter was used for the HRUs within each subbasin.

The second step of the automatic calibration using LUCA was storm-mode (hourly) calibration of the parameters listed in table 9. This method was useful in improving the simulation in headwater basins. Parameters for ungaged basins in the model were set at values calibrated from the nearest subbasin.

Table 8. Parameters calibrated in each step of the calibration process, with the model in daily mode.

[Dimensions: nmths, number of months = 12; nsub, number of subbasins = 145; nhru, number of hydrologic response units (HRUs) = 869; PRMS, Precipitation Runoff Modeling System]

Calibration data set	Objective function	PRMS parameters used to calibrate model state	Dimensions	Range	Parameter description	Comments
Volume of storm period	Absolute Difference	rain_sub_adj	nmths x nsub	0–3	Adjustment factor for precipitation on rain days	Calibrate as a mean value. Combine calibrated values from each subbasin into a final parameter value. Interpolate to uncalibrated subbasins
		snow_sub_adj	nmths x nsub	0–3	Adjustment factor for precipitation on snow days	
Daily Values during storm periods	$NRMSE_d$	gwflow_coef	nhru	Based on observed	Groundwater routing coefficient	Calibrate as a mean value. Combine calibrated values from each subbasin into a final parameter value. Interpolate to uncalibrated subbasins HRUs
		gwstor_init	nhru	Based on observed	Storage in each GW reservoir at beginning of run	
		smidx_coef	nhru	0.0001–1	Coefficient in non-linear surface runoff contributing area algorithm	
		smidx_exp	nhru	0.2–0.8	Exponent in on-linear surface runoff contribution area algorithm	
		soil_moist_max	nhru	0–20	Maximum available water holding capacity of soil profile	
		soil_rechr_max	nhru	0–20	Maximum available water holding capacity for soil recharge zone	
		soil2gw_max	nhru	0.0001–0.5	Maximum rate of soil water excess moving to groundwater	

Table 9. Parameters calibrated in each step of the calibration process, with the model in storm mode.

Calibration data set	Objective function	PRMS parameters used to calibrate model state	Dimensions	Range	Parameter description	Comments
Values during storm periods	$NRMSE_h$	kpar	nhru	0–5	Hydraulic conductivity of the transmission zone	Calibrate as a mean value. Combine calibrated values from each subbasin into a final parameter value.
		psp	nhru	0.1–25	Moisture deficit times capillary drive	
		mf_max	nhru	0.5–8	Maximum melt factor	
		mf_min	nhru	0.1–4	Minimum melt factor	
		wind_adjust	nhru	0.02–1	Rate of melt due to wind effects	

An iterative manual calibration procedure was also used for downstream subbasins and ungaged subbasins. Simulated local inflows computed by PRMS were used with the HEC-ResSim reservoir simulation and flow-routing model component to compute main-stem flows at streamgage locations. On the basis of the comparison between simulated and observed flows at a streamgage, the precipitation adjustment factors for the subbasin providing local inflow above the streamgage were calibrated. Subbasin precipitation adjustment factors were calibrated in this manner proceeding downstream in the basin. This method improved the match between simulated and observed flow volumes but did not substantially affect the shape of simulated hydrographs.

The PRMS model was judged to be adequately calibrated for the generation of reservoir inflows, local inflows and unregulated tributary flows for input into the HEC-ResSim model to assess the effects of watershed characteristics on flooding in regulated tributaries and the main-stem Delaware River. The $NRMSE_h$ measure of model fit for hourly simulation periods is generally lower than the $NRMSE_d$ measure for daily simulation periods, indicating that the model is generally more accurate for the hourly simulation periods (table 7). This reflects the focus of the sequential model calibration effort on the hourly simulation of the time periods before, during, and after the three high-flow events. The simulated streamflow is generally more accurate for larger rivers and locations downstream of reservoirs, and less accurate for headwater or unregulated streams. This reflects the design of the model, by HRU and stream discretization, to provide a tool for managing streamflow in the large rivers in the study area, and to evaluate the effects of operations of the reservoirs. The observed and simulated mean and standard deviations of hourly streamflow further illustrate the model performance (table 10). In general, the simulated mean flows are larger than the observed mean flow, which may reflect the effect of manual adjustments to precipitation MPE data. These manual adjustments were made to visually improve the overall match between the simulated and observed storm volumes and may reflect a bias towards matching the high flows.

Simulated and observed hydrographs at streamgage locations also demonstrate the model's ability to reproduce streamflows that were observed during the flood event (figs. 10-15). Simulated hydrographs are smoother than observed hydrographs, suggesting that the model, using a 1-hour time step, does not capture all the temporal variability during the watershed hydrologic processes controlling streamflow. During calibration procedures, backwater effects on the stage at the Minisink Hills streamgage were identified, and the corresponding discharge data were removed from the observed record (fig. 10, for example). Overall, the visual match between observed and simulated hydrographs is better at streamgages on main rivers below reservoirs than at headwater and unregulated locations. These results are consistent with the model fit statistics.

The input data files for the calibrated PRMS model are available online at *http://pa.water.usgs.gov/drbfam*. This website also provides links to the software used in the model, the documentation, and other information related to the Flood-Analysis Model.

Table 10. Observed and simulated mean and standard deviation of hourly streamflow, in cubic feet per second, for streamgages used for model calibration for the Delaware River main-stem subbasin, Pennsylvania, New Jersey, and New York.

[Calibration periods: September 2004: September 13, 1:00 am to September 28, 12:00 am; April 2005: March 24, 1:00 am to April 15, 12:00 am; June 2006: June 19, 1:00 am to July 10, 12:00 am]

U.S. Geological Survey station number	Station name	Mean hourly streamflow (cubic feet per second)					
		September 2004		April 2005		June 2006	
		Observed	Simulated	Observed	Simulated	Observed	Simulated
01413500	East Branch Delaware River at Margaretville, N.Y.	1,050	1,720	1,540	1,900	1,250	1,790
01414000	Platte Kill at Dunraven, N.Y.	240	350	370	450	220	270
01414500	Mill Brook near Dunraven, N.Y.	140	250	210	260	120	200
01415000	Tremper Kill near Andes, N.Y.	190	290	270	360	200	300
01417500	East Branch Delaware River at Harvard, N.Y.	2,960	3,730	3,180	3,500	3,580	4,690
01420500	Beaver Kill at Cooks Falls, N.Y.	2,540	3,130	3,420	3,500	2,460	3,230
01421000	East Branch Delaware River at Fishs Eddy, N.Y.[1]	6,340	7,830	5,810	6,230	7,750	9,120
01423000	West Branch Delaware River at Walton, N.Y.	2,040	2,290	2,920	3,140	2,920	3,040
0142400103	Trout Creek near Trout Creek, N.Y.	180	250	170	220	210	280
01426000	Oquaga Creek at Deposit, N.Y.	510	750	910	860	780	1,000
01426500	West Branch Delaware River at Hale Eddy, N.Y.	3,960	4,530	5,260	5,710	5,550	6,310
01427510	Delaware River at Callicoon, N.Y.	14,200	17,310	18,390	19,210	19,170	21,490
01428500	Delaware River above Lackawaxen River near Barryville, N.Y.	16,080	19,030	20,520	21,330	13,690	17,140
01428750	West Branch Lackawaxen River near Aldenville, Pa.	260	310	620	580	900	800
01431500	Lackawaxen River at Hawley, Pa.	2,270	2,680	3,840	4,210	4,130	4,800
01432900	Mongaup River at Mongaup Valley, N.Y.	540	650	830	890	430	460
01434000	Delaware River at Port Jervis, N.Y.	22,950	27,030	30,520	31,650	27,390	32,400
01435000	Neversink River near Claryville, N.Y.	470	760	870	910	620	800
01436690	Neversink River at Bridgeville, N.Y.	820	1,050	2,040	2,390	1,120	1,690
01437500	Neversink River at Godeffroy, N.Y.	1,360	1,790	3,490	3,710	1,120	1,900
01438500	Delaware River at Montague, N.J.	26,220	30,080	35,690	37,260	30,010	35,120
01439500	Bush Kill at Shoemakers, Pa.	1,040	1,010	1,200	1,100	870	800
01440000	Flat Brook near Flatbrookville, N.J.	350	440	500	490	530	360
01442500	Brodhead Creek at Minisink Hills, Pa.	1,840	2,010	2,520	2,450	2,260	2,260
01443500	Paulins Kill at Blairstown, N.J.	660	740	930	920	490	480
01446500	Delaware River at Belvidere, N.J.	34,410	39,090	48,420	47,920	37,540	42,610
01447500	Lehigh River at Stoddartsville, Pa.	880	1,010	920	960	950	1,070
01447720	Tobyhanna Creek near Blakeslee, Pa.	1,240	1,410	1,370	1,320	1,340	1,350
01449000	Lehigh River at Lehighton, Pa.	4,400	5,890	5,990	5,630	5,910	6,500
01449360	Pohopoco Creek at Kresgeville, Pa.	360	360	440	410	340	310
01450500	Aquashicola Creek at Palmerton, Pa.	730	960	680	760	540	710
01451000	Lehigh River at Walnutport, Pa.	6,980	8,570	8,880	8,390	8,840	9,530
01452000	Jordan Creek at Allentown, Pa.	550	700	710	810	410	500
01453000	Lehigh River at Bethlehem, Pa.	8,680	10,750	11,690	10,720	10,470	11,090
01463500	Delaware River at Trenton, N.J.	45,990	58,000	62,560	66,800	49,910	61,600

[1] Includes record from discontinued gage 01420980.

Table 10. Observed and simulated mean and standard deviation of hourly streamflow, in cubic feet per second, for streamflow-gaging stations used for model calibration for the Delaware River main-stem subbasin, Pennsylvania, New Jersey, and New York.—Continued

[Calibration periods: September 2004: September 13, 1:00 am to September 28, 12:00 am; April 2005: March 24, 1:00 am to April 15, 12:00 am; June 2006: June 19, 1:00 am to July 10, 12:00 am]

U.S. Geological Survey station number	Standard deviation of hourly streamflow (cubic feet per second)					
	September 2004		April 2005		June 2006	
	Observed	Simulated	Observed	Simulated	Observed	Simulated
01413500	2,040	2,300	2,050	2,250	1,800	2,020
01414000	470	510	450	480	350	400
01414500	400	350	300	320	180	210
01415000	470	430	340	410	370	500
01417500	4,620	4,370	4,420	4,290	5,360	6,040
01420500	6,460	5,130	6,490	4,950	6,200	5,320
01421000	10,680	10,170	8,260	8,300	13,870	12,880
01423000	3,390	3,200	3,400	3,530	5,530	5,300
0142400103	390	410	250	270	480	540
01426000	1,240	1,160	930	980	2,240	1,880
01426500	4,150	4,550	5,140	5,220	8,860	9,820
01427510	22,260	20,750	21,520	21,450	31,740	31,570
01428500	24,680	22,750	23,740	23,420	21,570	23,340
01428750	520	430	1,260	890	1,740	1,490
01431500	3,710	3,350	4,180	4,010	6,400	6,230
01432900	940	960	1,140	1,220	680	710
01434000	32,570	29,960	33,030	31,360	41,790	43,120
01435000	880	980	1,780	1,130	1,220	970
01436690	1,400	1,220	3,730	3,240	2,000	1,690
01437500	1,530	1,530	4,920	4,560	2,000	2,070
01438500	37,170	32,170	41,180	37,570	47,010	45,790
01439500	1,210	1,240	1,140	1,330	1,050	1,250
01440000	660	560	530	520	400	420
01442500	2,740	3,190	3,270	3,820	4,730	4,440
01443500	880	910	750	990	480	450
01446500	43,770	37,070	50,170	44,880	54,120	53,900
01447500	1,750	1,780	1,150	1,290	1,850	2,080
01447720	2,190	2,170	1,990	1,970	2,490	2,080
01449000	3,690	4,540	3,360	3,700	5,720	5,600
01449360	420	450	390	470	400	450
01450500	1,270	1,350	750	830	760	740
01451000	6,610	6,920	5,500	5,380	8,980	8,590
01452000	1,230	1,210	1,020	880	670	720
01453000	9,700	9,540	7,610	7,420	10,450	10,510
01463500	51,090	49,250	54,650	53,980	61,820	66,780

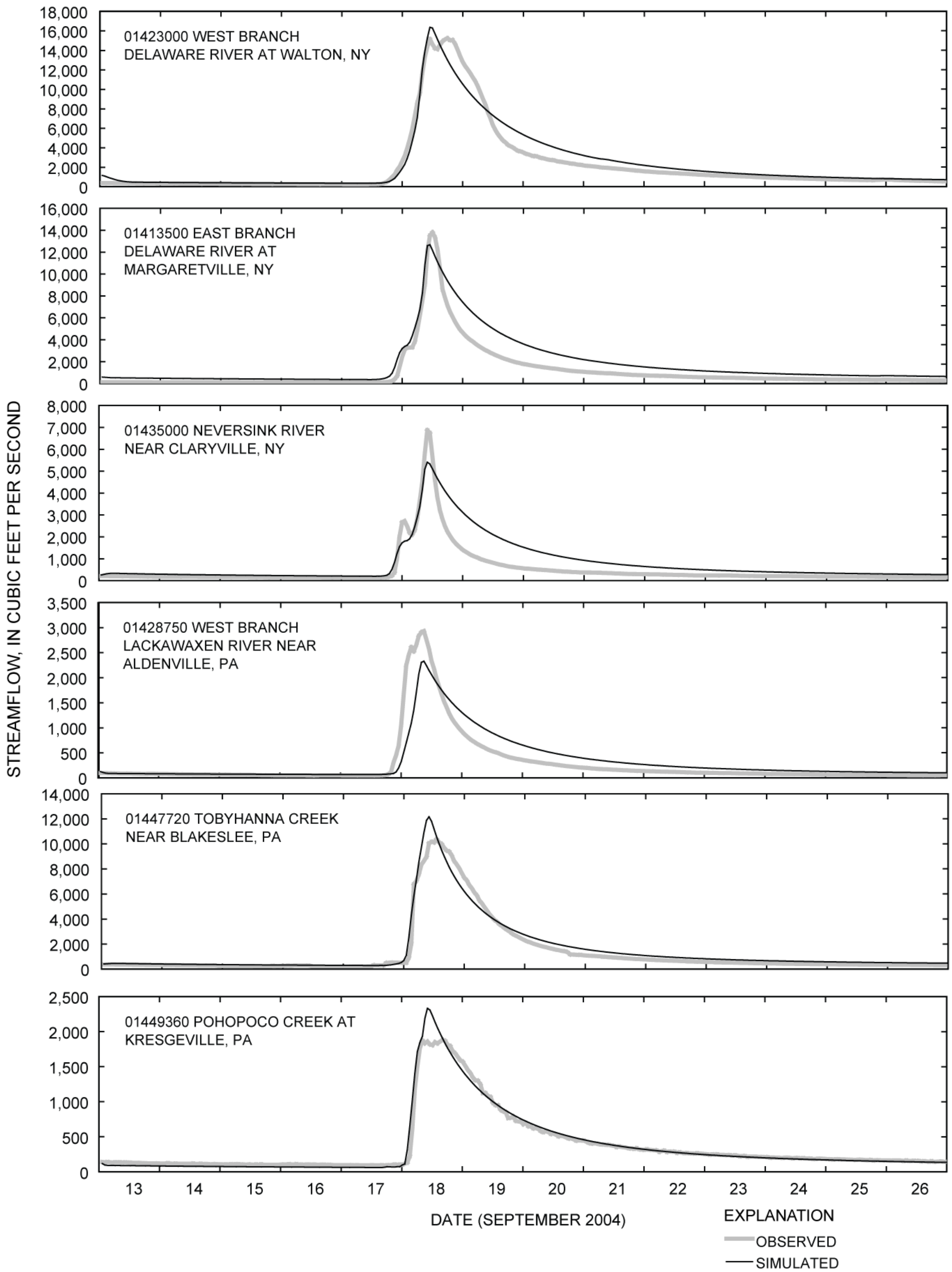

Figure 10. Simulated and observed streamflow, September 13 to 26, 2004, at selected U.S. Geological Survey streamgages in the Delaware River main-stem subbasin, Pennsylvania, New Jersey, and New York. Streamflow at these locations is not regulated by reservoirs simulated in HEC-ResSim.

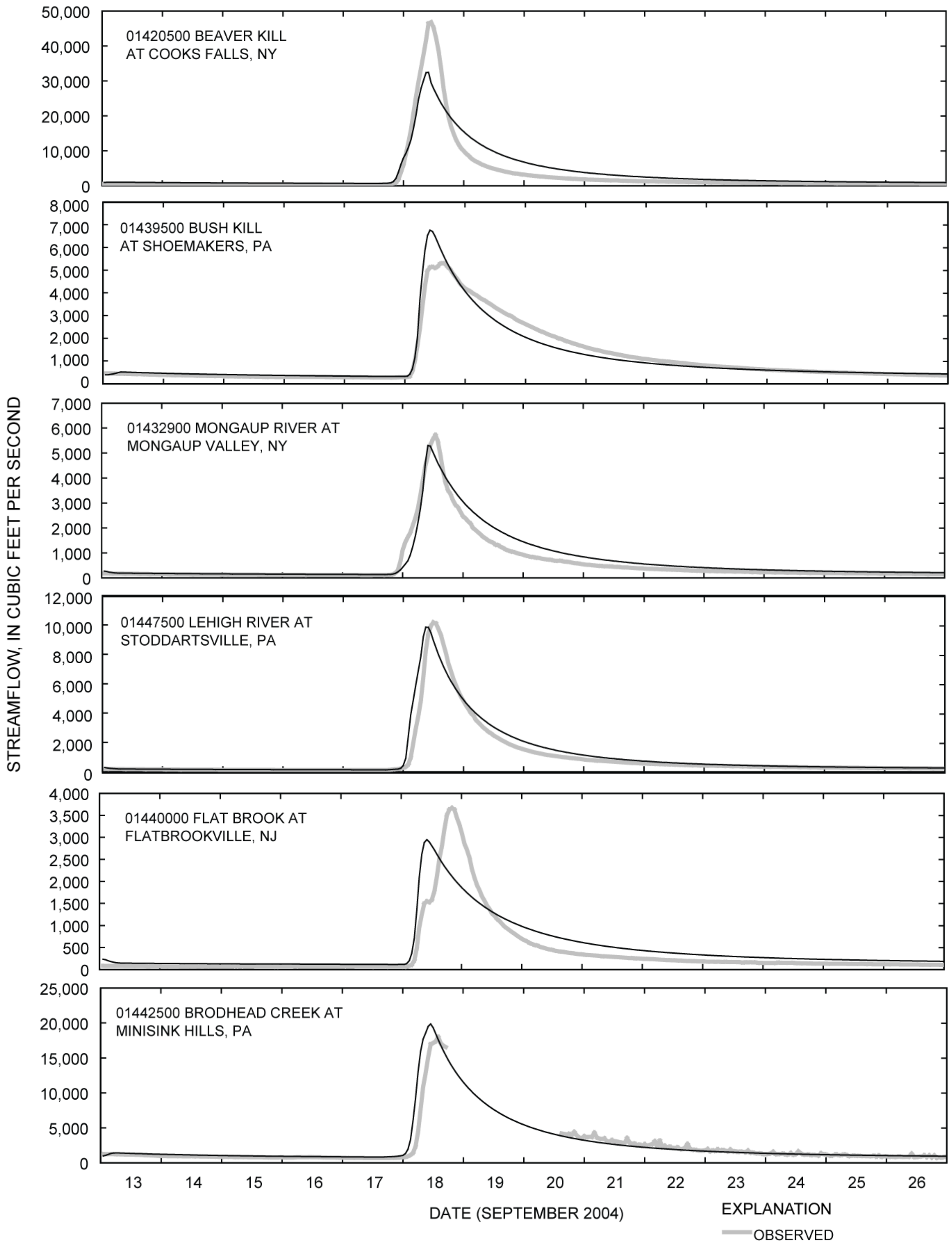

Figure 10. Simulated and observed streamflow, September 13 to 26, 2004, at selected U.S. Geological Survey streamgages in the Delaware River main-stem subbasin, Pennsylvania, New Jersey, and New York. Streamflow at these locations is not regulated by reservoirs simulated in HEC-ResSim. –Continued Observed data affected by backwater removed from Minisink Hills record.

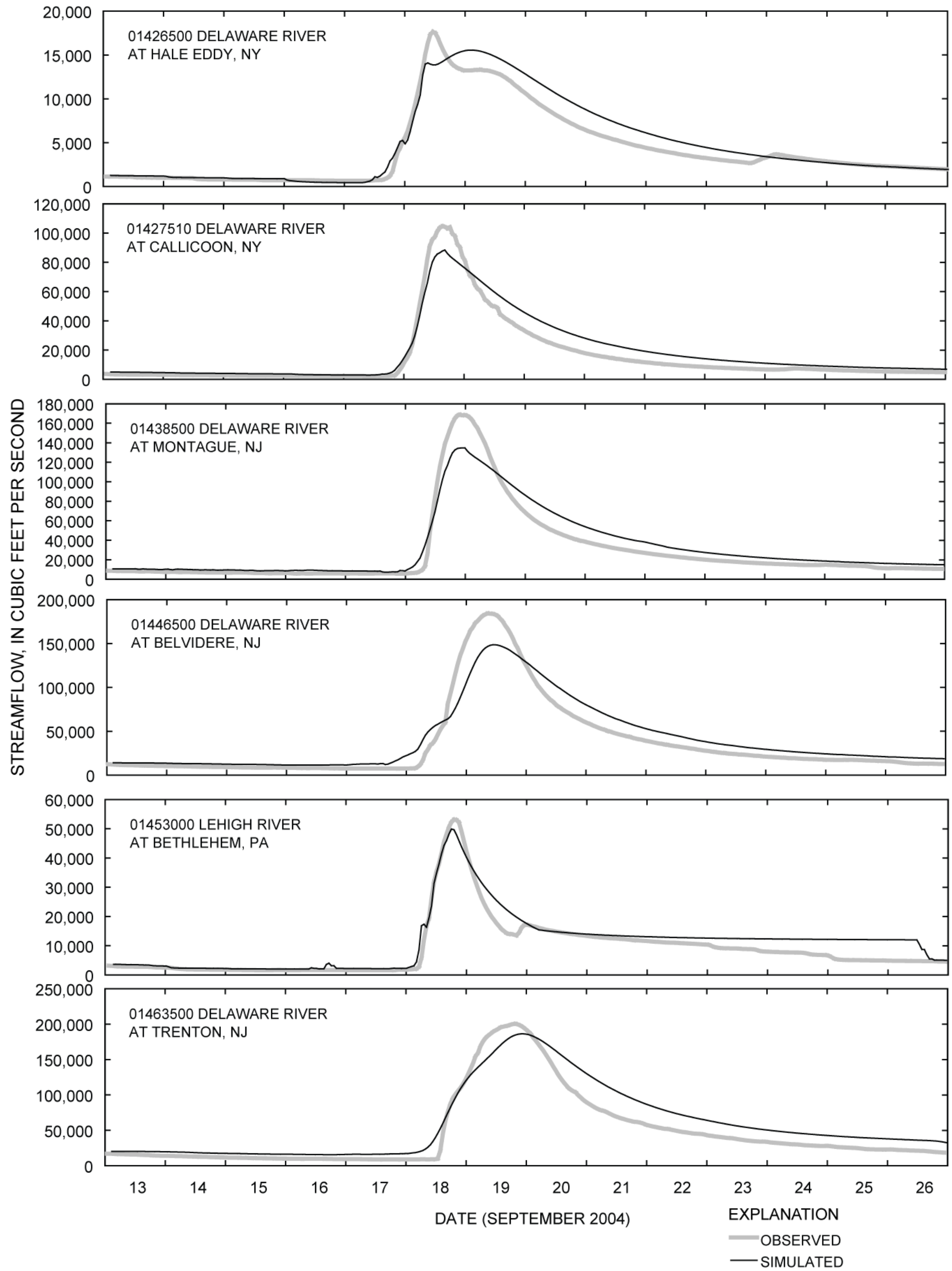

Figure 11. Simulated and observed streamflow, September 13 to 26, 2004, at selected U.S. Geological Survey streamgages below reservoirs in the Delaware River main-stem subbasin, Pennsylvania, New Jersey, and New York. Simulated streamflow is from HEC-ResSim reservoir and routing model using runoff and reservoir inflow from the PRMS model (Joan Klipsch, U.S. Army Corps of Engineers, written commun., May 4, 2009)

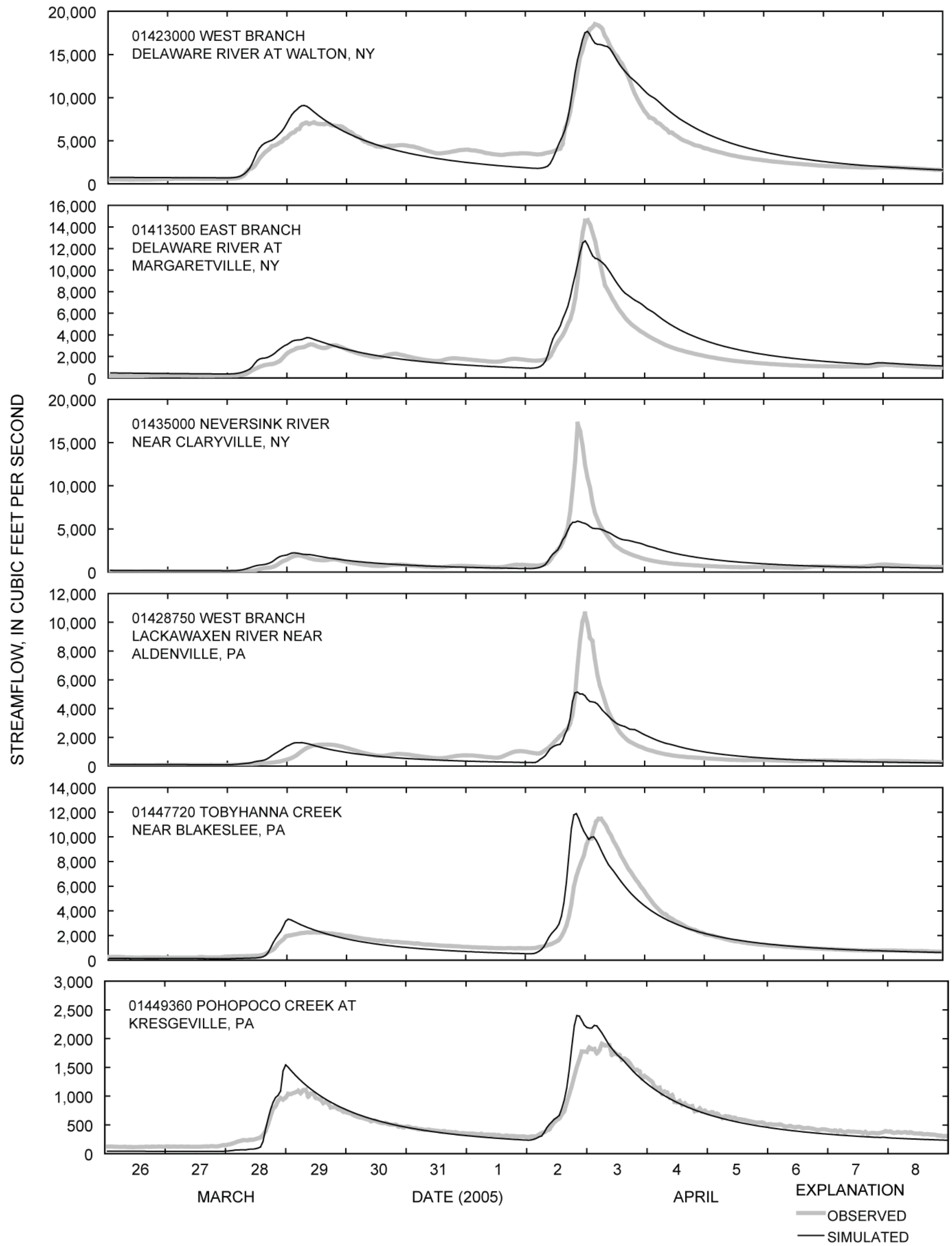

Figure 12. Simulated and observed streamflow, March 26 to April 8, 2005, at selected U.S. Geological Survey streamgages in the Delaware River main-stem subbasin, Pennsylvania, New Jersey, and New York. Streamflow at these locations is not regulated by reservoirs simulated in HEC-ResSim.

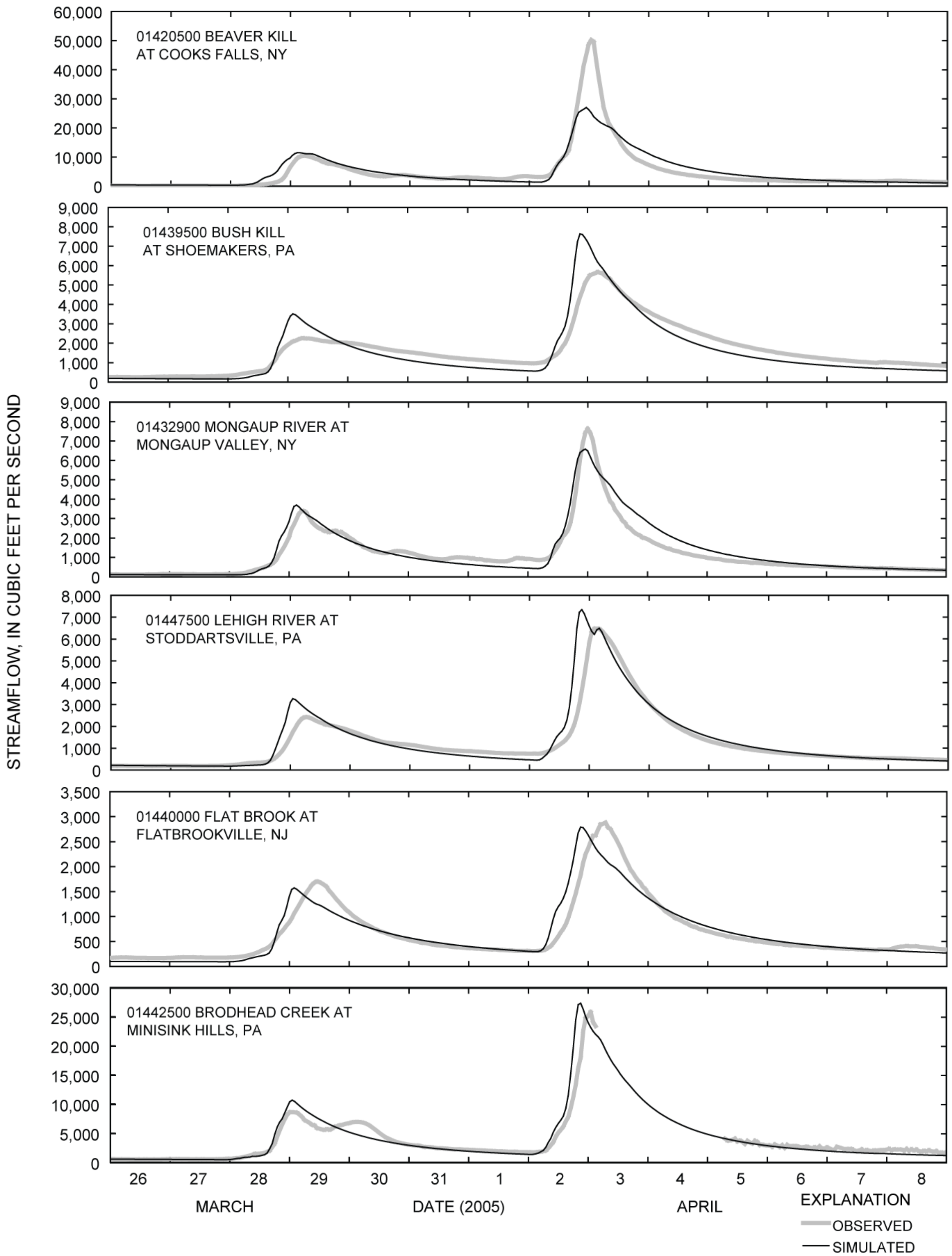

Figure 12. Simulated and observed streamflow, March 26 to April 8, 2005, at selected U.S. Geological Survey streamgages in the Delaware River main-stem subbasin, Pennsylvania, New Jersey, and New York. Streamflow at these locations is not regulated by reservoirs simulated in HEC-ResSim. –Continued
Observed data affected by backwater removed from Minisink Hills record.

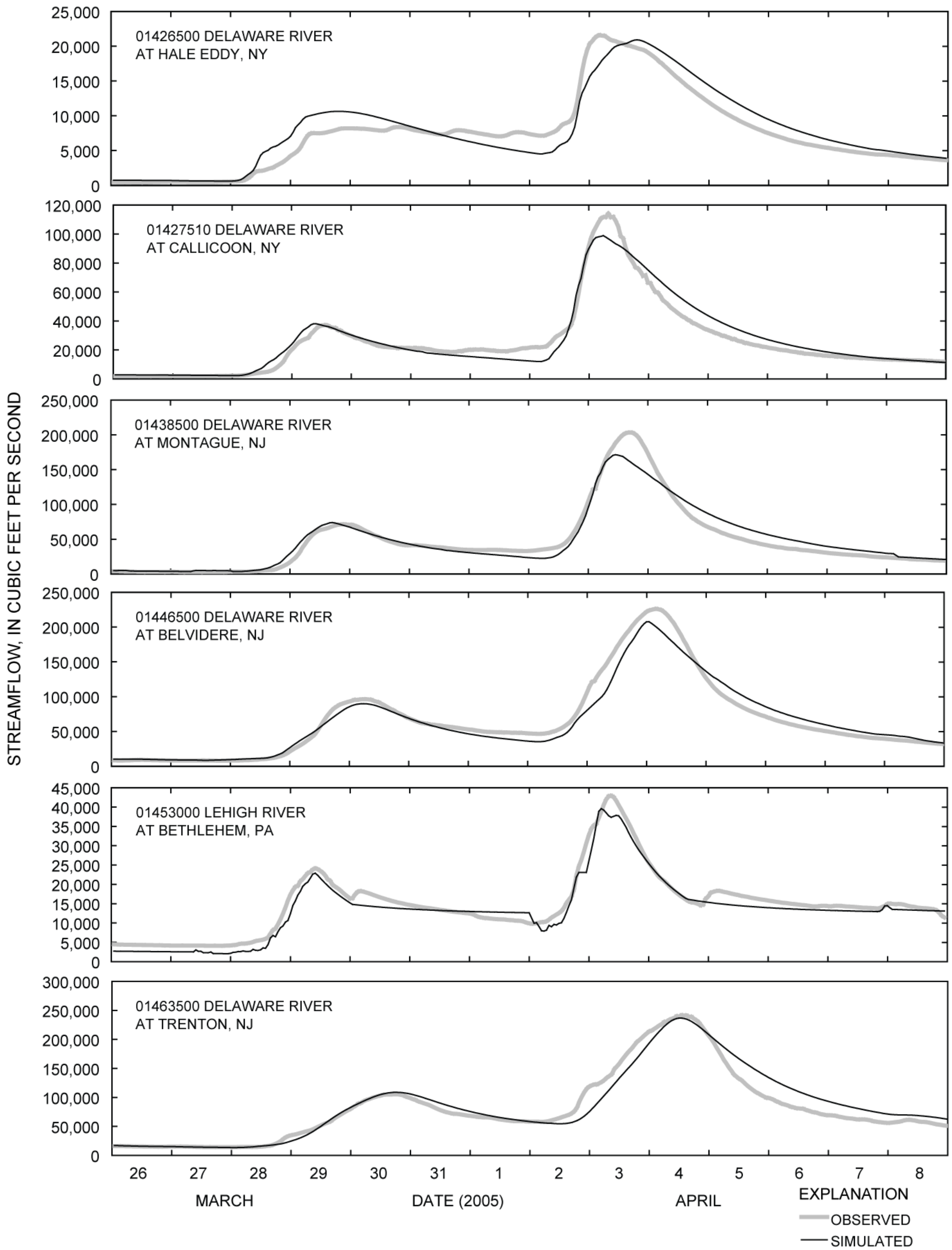

Figure 13. Simulated and observed streamflow, March 26 to April 8, 2005, at selected U.S. Geological Survey streamgages below reservoirs in the Delaware River main-stem subbasin, Pennsylvania, New Jersey, and New York. Simulated streamflow is from HEC-ResSim reservoir and routing model using runoff and reservoir inflow from the PRMS model (Joan Klipsch, U.S. Army Corps of Engineers, written commun., May 4, 2009)

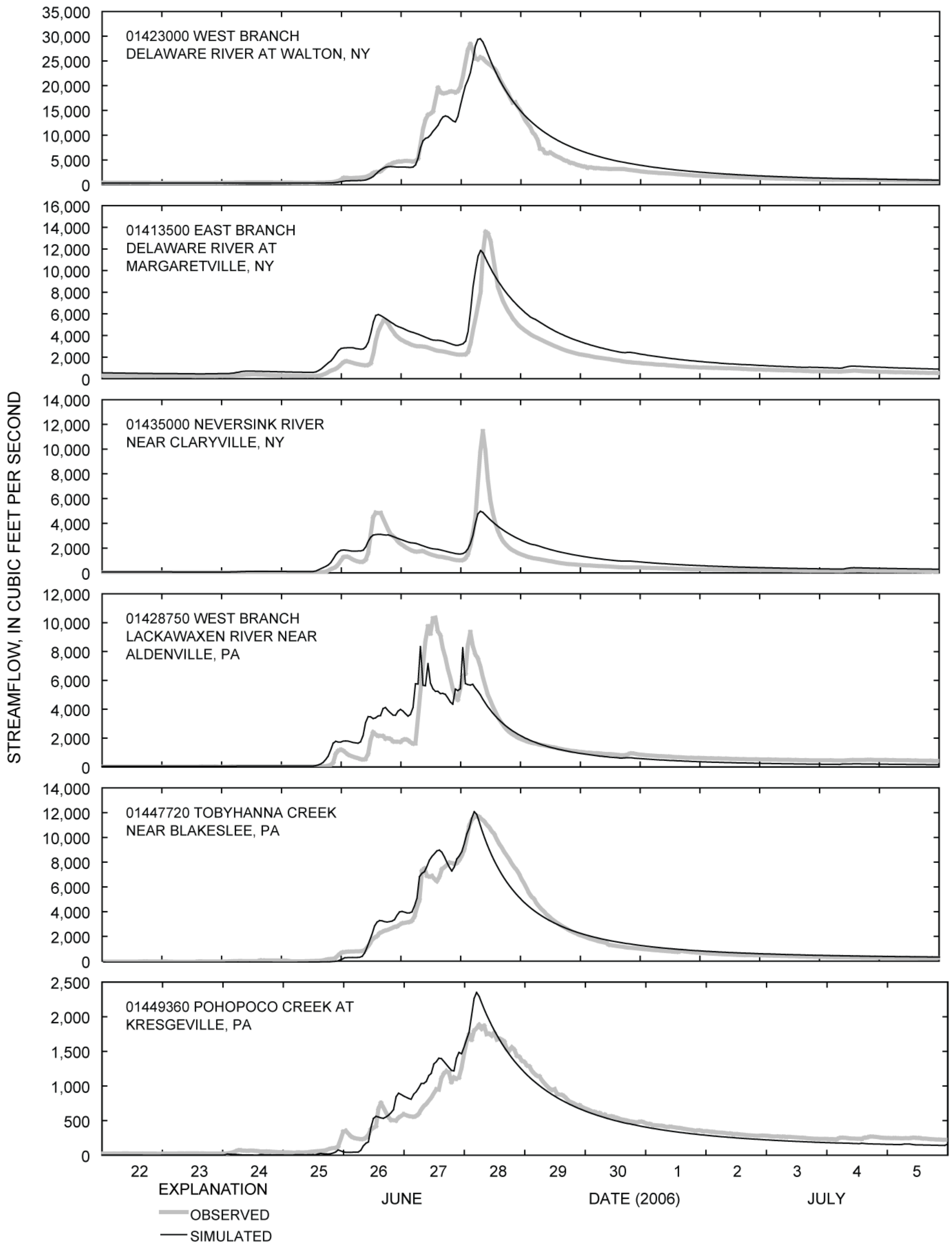

Figure 14. Simulated and observed streamflow, June 22 to July 5, 2006, at selected U.S. Geological Survey streamgages in the Delaware River main-stem subbasin, Pennsylvania, New Jersey, and New York. Streamflow at these locations is not regulated by reservoirs simulated in HEC-ResSim.

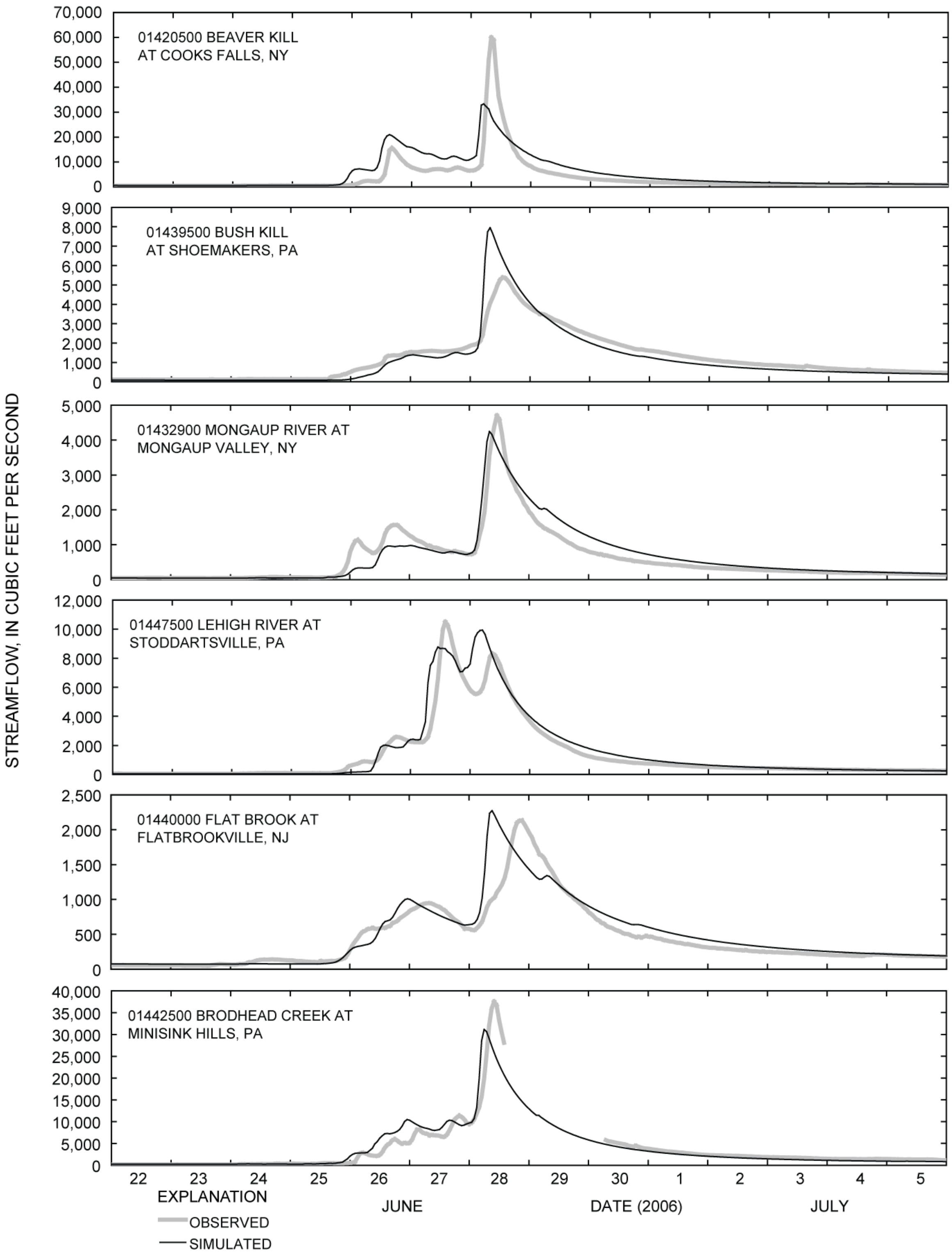

Figure 14. Simulated and observed streamflow, June 22 to July 5, 2006, at selected U.S. Geological Survey streamgages in the Delaware River main-stem subbasin, Pennsylvania, New Jersey, and New York. Streamflow at these locations is not regulated by reservoirs simulated in HEC-ResSim.–Continued Observed data affected by backwater removed from Minisink Hills record.

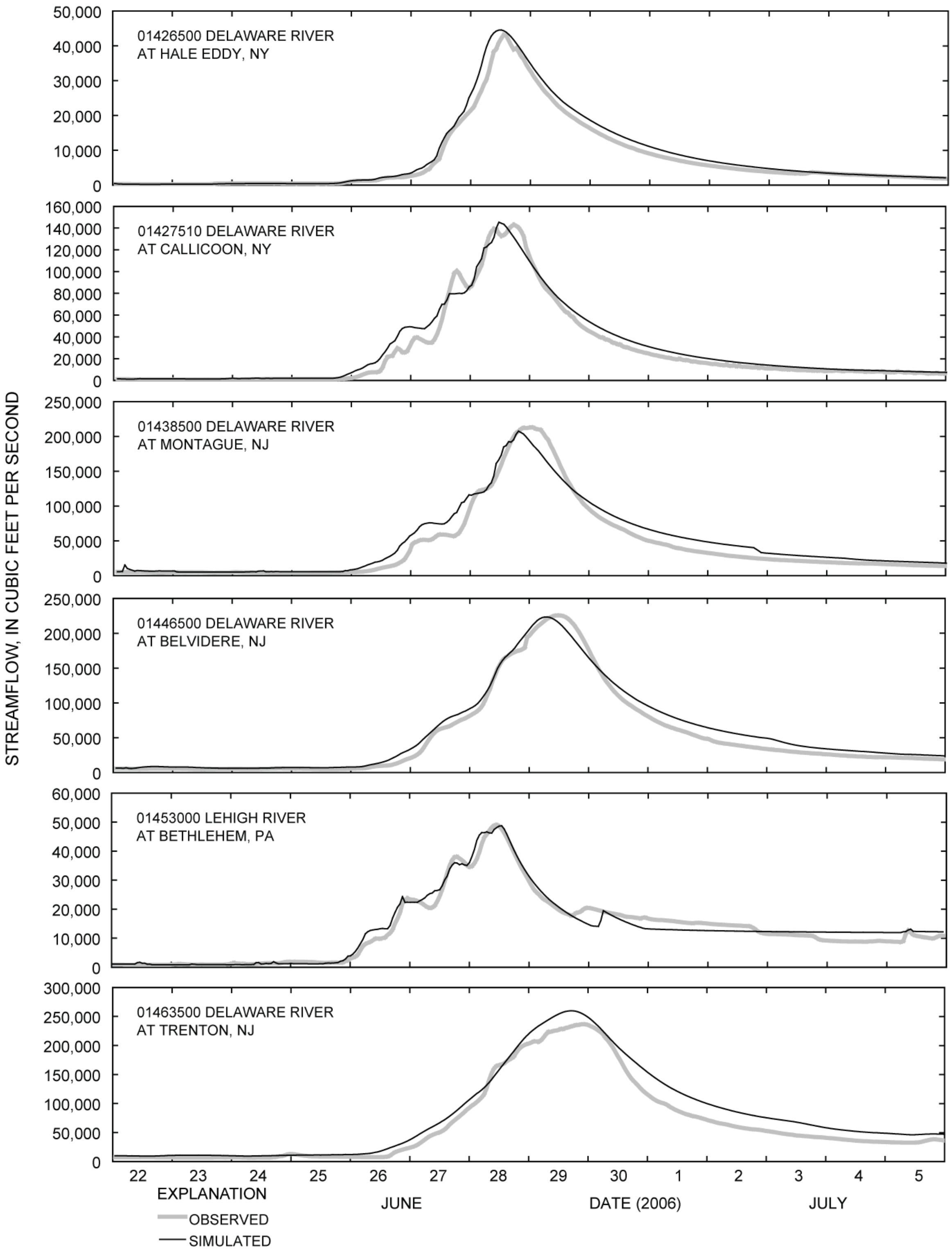

Figure 15. Simulated and observed streamflow, June 22 to July 5, 2006, at selected U.S. Geological Survey streamgages below reservoirs in the Delaware River main-stem subbasin, Pennsylvania, New Jersey, and New York. Simulated streamflows are from HEC-ResSim reservoir and routing model using runoff and reservoir inflow from the PRMS model (Joan Klipsch, U.S. Army Corps of Engineers, written commun., May 4, 2009)

Limitations

The PRMS model of the Delaware River subbasin draining to Trenton, N.J., simulates runoff to reservoirs and local runoff for input into the HEC-ResSim model to compare the effects of different watershed conditions on flows in large rivers within the study area during flooding. The model is limited, however, by the following: spatial resolution, data gaps, model simplifications, errors in precipitation and temperature input data, errors in streamflow calibration data, and the focus of calibration on peak flows.

The large model area caused some computational difficulties during discretization and GIS processing. These difficulties limited the minimum size of HRUs and the resolution of the DEM used. Precipitation in the study area is correlated with elevation; higher precipitation amounts are related to higher elevations. Furthermore, the change in elevation, or slope, is a primary factor in runoff characteristics. Hence, discretization with smaller HRUs and more accurate elevations and slopes may improve the simulation results, especially in headwater streams.

Several data gaps exist that affect model accuracy. Stages at the Minisink Hills streamgage are affected by backwater during high-flow events and, hence, cannot be used to estimate discharge in the tributary during these periods. A few other streamgages were inoperative during peak flows because the streamgage equipment was inundated. Substantial portions of the streamflow into many of the major reservoirs in the study area are not measured. Some streamgages, especially on the main-stem Delaware River, are operated as stage-only streamgages, and the associated rating curve to convert stage into discharge is less accurate than at fully maintained streamgages. In addition, missing data and artifacts were identified in climate data, including MPE precipitation.

This model is judged adequate for providing reservoir inflows, local inflows and unregulated tributary flows for input into the HEC-ResSim model to assess the impacts of watershed conditions on flows in the regulated tributaries and main stem of the Delaware River during high-flow events. Other uses of the model may require additional development or calibration. The model calibration focused on time periods before, during, and after the three extreme high-flow events; the model will be less accurate for simulations during other conditions.

Suggestions for Model Application

Suggested use of the PRMS model is to provide runoff and streamflow information throughout the study area for use in a reservoir-operation model, HEC-ResSim, documented separately. The Flood-Analysis Model, integrating the PRMS and HEC-ResSim models, was developed to be used to evaluate the impacts of both basin hydrology and reservoir operations on downstream flood discharges during the three high-flow events and was developed as a planning tool. Simulation results with existing or historic conditions can be compared to simulation results using alternative conditions, to evaluate the impact of those alternative conditions on downstream flows in large rivers. In this approach, the model errors common to both simulation results have minimal impact on the relative differences between the simulations. This model was not developed as a forecasting tool for realtime prediction of floods on the Delaware River.

The PRMS model provides simulated hydrologic conditions throughout the watershed, as discretized by the model HRUs. An example of the output from the PRMS model is the soil moisture in the watershed, which acts as a reservoir to store and release water (fig. 16). The model also computes incremental runoff for simulated stream segments (fig. 17). These variables change hourly during the storm-mode simulation. Many other model variables can be examined through the model output files and the user interface provided.

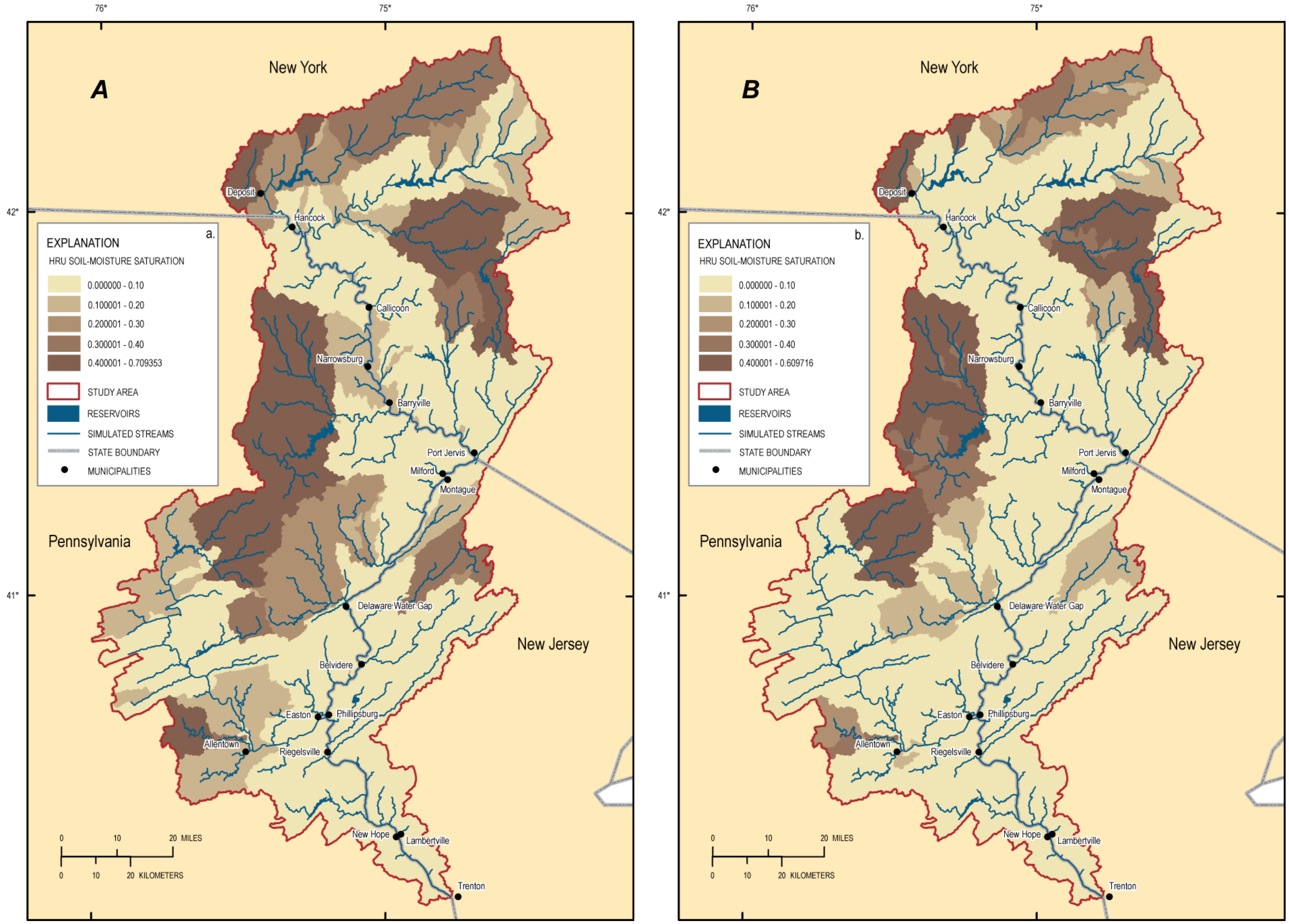

Figure 16. Simulated soil-moisture saturation at noon on *A*) March 26, 2005, and *B*) June 23, 2006, for model hydrologic response units (HRUs) for the Delaware River main-stem subbasin, Pennsylvania, New Jersey, and New York.

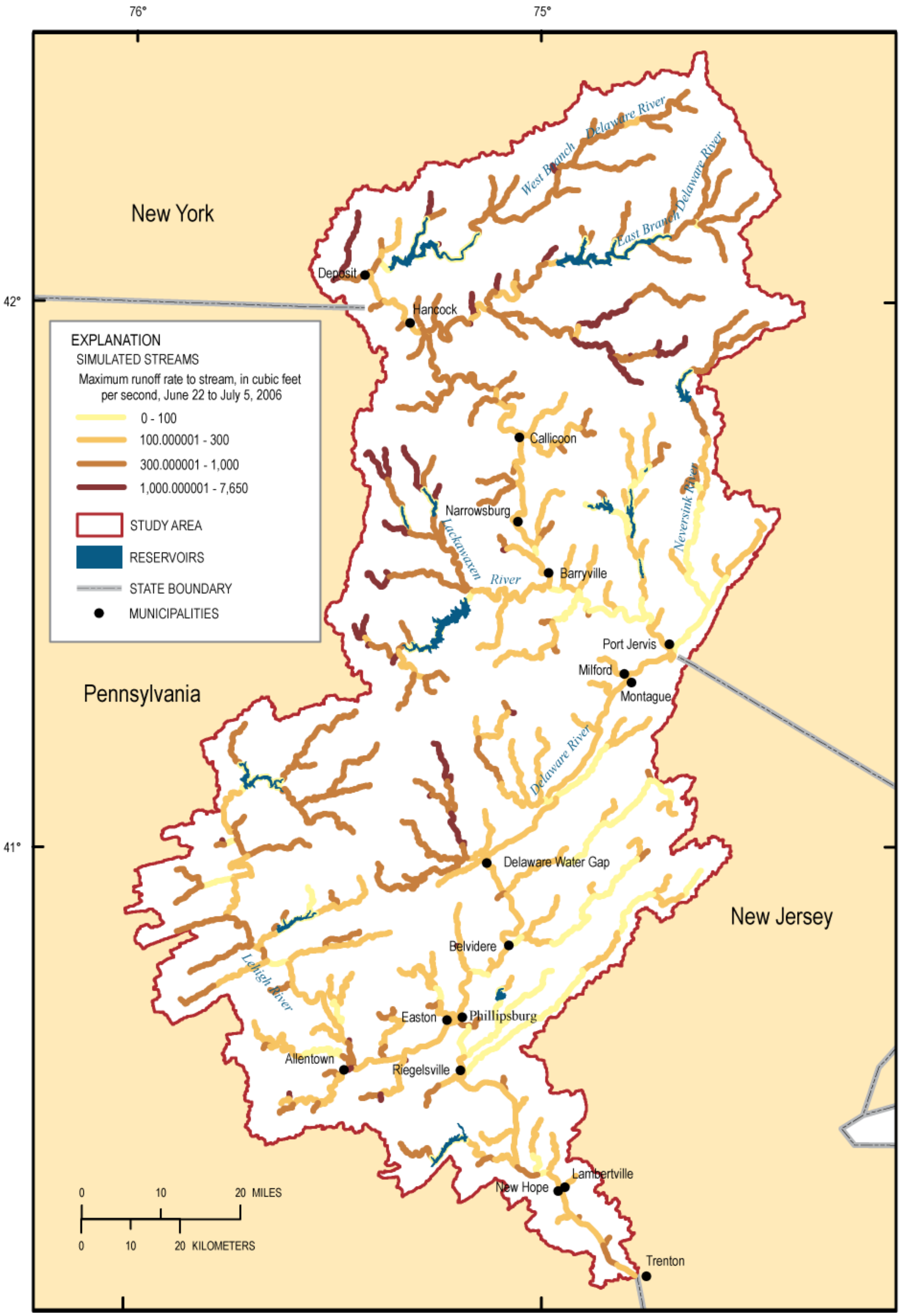

Figure 17. Simulated maximum runoff rate during June 22 to July 5, 2006, to model stream segments for the Delaware River main-stem subbasin, Pennsylvania, New Jersey, and New York.

The Flood-Analysis Model may be useful as a planning tool to evaluate the effects of watershed conditions on flood discharges on large rivers in the Delaware River main-stem subbasin. The model can be used to predict streamflow under different past climate conditions, provided those are reasonably close to the climate of the calibration events. Model results using different past climate records can help understand the watershed response to different storm events. However, the calibration described in this report focuses on runoff during three flood events. Applications for non-flood events, or for flood events having different conditions than the three events considered here, may require additional calibration.

As a planning tool, the model may also be useful for simulation of the change in high flows for cases with different watershed parameters. To assist with land-use planning, for example, an alternative model could be developed with PRMS model parameters that could be adjusted to account for hypothetical changes in land use. The high flows simulated using such an alternative model could be compared to the calibrated model results, and the differences caused in the model by the changes in land-use parameters could be used to inform land-use planning decisions. However, the alternative or adjusted parameters needed to represent the land-use changes in this example would need to be determined by an expert user, using procedures beyond those developed for this study. The validity of such an application would rest on the validity of the user-specified parameters. In addition, the simulated hydrologic conditions in such an alternative case may extend beyond the conditions used here for model calibration, introducing additional error in the simulation results.

An appropriate use of the model for planning purposes would be to compare model results to model results, as input to make decisions about alternative management of the watershed. For example, an analysis of the effect of land-use change on streamflow would compare the results of model simulations for two different cases of land-use conditions. It would not be appropriate to conduct such an analysis by comparing simulated streamflow, with hypothetical land use, to measured streamflow, because such a comparison would include errors in the simulated streamflow that are present only in the model results. By comparing model results to model results, the impact of the unavoidable model errors on the differences is minimized. This use is similar to the use of the daily flow model OASIS to inform the decision-making process by DRBC (Quinodoz, 2006).

Summary

To evaluate the impact of reservoir levels and other factors on flooding, the DRBC, USGS, HEC, and NWS developed a Flood-Analysis Model for the Delaware River. The primary components of the model are a rainfall-runoff component (the PRMS model) and a reservoir and streamflow routing component (the HEC-ResSim model). This report describes the rainfall-runoff model component, which uses a modified version of the PRMS software. 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. The PRMS model simulates time periods associated with main-stem flooding that occurred in September 2004, April 2005, and June 2006.

The study area was the 6,780-mi^2 watershed of the Delaware River in the states of Pennsylvania, New Jersey, and New York that drains to Trenton, N.J. A geospatial database was created for use with a GIS to assist model discretization, determine land-surface characterization, and estimate model parameters. The USGS NED at 100-m resolution was used for model discretization into 452 stream segments and 869 HRUs. In addition, geospatial processing was used to estimate initial model parameters from the DEM and other data layers, including land use. Climate data for point stations were obtained from multiple sources. These sources included daily data for 22 NWS Coop network stations, hourly data for 15 stations from the NCDC, hourly data for 1 station from the NWS Middle Atlantic

River Forecast Center records, and daily and hourly data for 7 stations operated by the NYCDEP. The NWS radar-based Multisensor Precipitation Estimate data set was used to compute daily precipitation in the study area for 2001-2007 and to compute hourly precipitation for storm periods.

Calibration of the PRMS model was performed using the LUCA model calibration tool, as well as manual adjustments. The general goal of the calibration procedure was to minimize the difference between streamflow measured at USGS streamgages and the corresponding streamflow simulated by the model. Daily streamflow data from 42 USGS streamgages were acquired for use in model calibration. The streamflow data represented areas draining from 20.2 to 6,780 mi^2. The model was judged to be adequately calibrated for generation of reservoir inflows, local inflows and unregulated tributary flows for input into the HEC-ResSim model to assess the effects of watershed characteristics on regulated tributary and main stem Delaware River flows during floods. Model uncertainty is lower for streamflow on major rivers below reservoirs, and higher for smaller unregulated streams.

The PRMS model simulates runoff and reservoir inflows for input into the HEC-ResSim model to assess the impacts of watershed conditions on flows in the regulated tributaries and main stem of the Delaware River watershed draining to Trenton, N.J. during high flow events. Suggested application of the PRMS model is as a planning tool, in conjunction with the reservoir-simulation component, the HEC-ResSim model, of the Flood-Analysis Model. Differences in simulation results for different model input may be useful in evaluating alternative management of the land and water resources of the basin. Accuracy of the model is limited by the following: spatial resolution, data gaps, model simplifications, errors in precipitation and temperature input data, errors in streamflow calibration data, and the focus of calibration on peak flows.

Acknowledgments

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Appendix – Documentation of PRMS Modules Modified for This Study

There are three modules that were created or modified for this study. These modules are documented herein.

Module climate_hru_prms.f

NAME

climate_hru_prms.f

SPECIAL FEATURES

This is a new module.

MODULE PROCESS (TYPE)

Climate

DEFINITION

Reads input precipitation and temperature variables from the designated data files.

KEYWORDS

CREATION DATE

January 2009

PARAMETERS DECLARED

Tmax_allsnow – Monthly maximum air temperature at which precipitation is all snow for the HRU.
Hru_subbasin – Index of subbasin number for each HRU.
Hru_area – Area of each HRU.
Tmax_allrain – Monthly minimum air temperature at an HRU that results in all precipitation during a day being rain
Rain_sub_adj – Monthly factor as a decimal fraction used to adjust rain values, by subbasin.
Snow_sub_adj – Monthly factor as a decimal fraction used to adjust snow values, by subbasin.

VARIABLES DECLARED

Basin_temp – Basin area-weighted temperature for time step < 24.
Basin_tmax – Basin area-weighted daily maximum temperature.
Basin_tmin – Basin area-weighted daily minimum temperature.
Solrad_tmax – Basin daily maximum temperature for use with solrad.
Solrad_tmin – Basin daily minimum temperature for use with solrad.
Tmaxf – HRU adjusted daily maximum temperature, degrees F.
Tminf – HRU adjusted daily minimum temperature, degrees F.
Tavgf – HRU adjusted daily average temperature, degrees F.
Tmaxc – HRU adjusted daily maximum temperature, degrees C.
Tminc – HRU adjusted daily minimum temperature, degrees C.
Tavgc – HRU adjusted daily average temperature, degrees C.
Tempf – HRU adjusted temperature for time step < 24, degrees F.
Tempc – HRU adjusted temperature for time step < 24, degrees C.
Tmax – Observed daily maximum temperature at each measurement station, in degrees Fahrenheit.

`Tmin` – Observed daily minimum temperature at each measurement station, in degrees Fahrenheit.
`Newsnow` – New snow on HRU (0=no; 1=yes).
`Pptmix` – Precipitation mixture (0=no; 1=yes).
`Basin_ppt` – Area weighted adjusted average precipitation for basin, in inches.
`Basin_obs_ppt` – Area weighted measured average precipitation for basin, in inches.
`Basin_rain` – Area weighted adjusted average rain for basin, in inches.
`Basin_snow` – Area weighted adjusted average snow for basin, in inches.
`Hru_ppt` – Adjusted precipitation on each HRU, in inches.
`Hru_rain` – Computed rain on each HRU, in inches.
`Hru_snow` – Computed snow on each HRU, in inches.
`Prmx` – Proportion of rain in a mixed event, in inches.

EXTERNAL VARIABLES USED

`Route_on` – Simulate flow routing (0=no; 1=yes).
`Newday` – Time step is first time step for a day (0=no; 1=yes).
`Active_hrus` – Number of active HRUs.
`Hru_route_order` – Routing order of HRUs.
`Basin_area_inv` – Inverse of total basin area as sum of HRU areas, in acres^{-1}.

DESCRIPTION

This module reads daily and hourly precipitation and temperature data by HRU and makes that data available to other modules. Input data file names are hardcoded in the module.

REFERENCES

none

DEVELOPER NAME AND ADDRESS

R. Steve Regan
U.S. Geological Survey
Box 25046, MS 412
Denver Federal Center
Lakewood, CO 80225

Module local_flow_drbc.f

NAME

`local_flow_drbc.f`

SPECIAL FEATURES

This is a new module.

MODULE PROCESS (TYPE)

Output

DEFINITION

Accumulates and outputs flows for calibration and use by other models.

KEYWORDS

CREATION DATE

January 2009

PARAMETERS DECLARED

`Hru_area` – Area of each HRU.
`Dss_output_file` – Name of DSS output file.
`Csv_output_file` – Name of comma-delimited output file.

VARIABLES DECLARED

`Locs` – Output identifiers for DSS output.
`Loc_flows` – Accumulated flows for DSS output.
`Strm_flows` – Storm mode flows for calibration output.
`Ifltab` – File identifier for DSS file.
`Nowtime` – Time formatted for DSS file.
`Jul_day` – Julian day.
`Ierr` – Error flag for DSS output process.
`Nsegment` – Number of output segments for DSS file.
`Cpath` – Path identifier for DSS output.
`Ca-f` – Identifiers (DSS “part”) A through F for DSS output.

EXTERNAL VARIABLES USED

`Route_on` – Simulate flow routing (0=no; 1=yes).
`Sub_cfs` – Subbasin flow (cfs).
`Sub_inq` – Instantaneous subbasin flow (cfs).
`Hru_ppt` – Precipitation on HRU (inch).
`Runoff` – Observed gage flow (cfs)

`Q_chan` – Flow at outlet of channel (cfs).
`Qinlat_chan_ts` – Time step lateral inflow to channel (cfs).
`Q_chan_timestep` – Time step flow at outlet of channel (cfs).
`Qin_instant` – Instantaneous flow at inlet of channel (cfs).
`Contrib_area_chan` – Channel contributing drainage area (acres).
`Hortonian_lakes` – Hortonian runoff to lake HRU (cfs).
`Strm_seg_in` – Index of stream segments that flow to current segment.
`Lakein_sz` – Soil zone runoff to lake HRU (cfs).
`Lakein_gw` – Groundwater runoff to lake HRU (cfs).

DESCRIPTION

This module accumulates flows for calibration and use by other models. Calibration values use observed reservoir outflows instead of simulated reservoir outflows because reservoirs are not simulated in the present model. Reservoir inflows, local runoff, and tributary flows are output to a HEC-DSS format file for use in a separate reservoir simulation and downstream flow routing model using HEC-ResSim. Flow accumulations, output identifiers, and file names are hardcoded in the module.

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DEVELOPER NAME AND ADDRESS

R. Steve Regan
U.S. Geological Survey
Box 25046, MS 412
Denver Federal Center
Lakewood, CO 80225

Module snow17_st.f

NAME

`snow17_st.f`

SPECIAL FEATURES

This is a port of the existing SNOW-17 algorithm to PRMS. No changes were made to the algorithm or existing code.

MODULE PROCESS (TYPE)

Snow

DEFINITION

Snow accumulation and ablation model.

KEYWORDS

CREATION DATE

January 2009

PARAMETERS DECLARED

`SCF` – The multiplying factor which adjusts precipitation that is determined to be in the form of snow. SCF primarily accounts for gage catch deficiencies, but also implicitly includes the net effect of vapor transfer (sublimation and condensation, including from intercepted and blowing snow) and transfers across areal divides.

`MFMAX` – Maximum melt factor during non-rain periods – assumed to occur on June 21st (mm•°C-1• 6 hr-1).

`MFMIN` – Minimum melt factor during non-rain periods – assumed to occur on December 21st (mm•°C-1• 6 hr-1).

`UADJ` – The average wind function during rain-on-snow periods (mm•mb-1). UADJ is only a major parameter when there are fairly frequent rain-on-snow events with relatively warm temperatures.

`SI` – The mean areal water equivalent above which there is always 100 percent areal snow cover (mm). SI is not a major parameter when the model is applied at a point location or when significant bare ground appears soon after melt begins no matter the magnitude of the snow cover.

`Area Depletion Curve` – Curve that defines the areal extent of the snow cover as a function of how much of the original snow cover remains after significant bare ground shows up. The areal depletion curve also implicitly accounts for the reduction in the mean areal melt rate that occurs as less of the area is covered by snow. Generally not needed for a point location.

NMF – Maximum negative melt factor (mm•°C-1•6 hr-1). The negative melt factor has the same seasonal variation as the non-rain melt factor, thus the maximum value is assumed to occur on June 21st.

TIPM – Antecedent temperature index parameter (real – range is 0.01 to 1.0). Controls how much weight is put on temperatures from previous time intervals when computing ATI. The smaller the value of TIPM, the more previous time intervals are weighted.

PXTEMP – The temperature that separates rain from snow (°C). If the air temperature is less than or equal to PXTEMP, the precipitation is assumed to be in the form of snow. The PXTEMP parameter, as defined for SNOW-17, is not used if a rain-snow elevation time series is used to determine the form of precipitation.

MBASE – Base temperature for snowmelt computations during non-rain periods (°C). Typically a value of 0°C is used.

PLWHC – Percent liquid water holding capacity (decimal fraction). Indicates the maximum amount of liquid water, as a fraction of the ice portion of the snow, that can be held against gravity drainage (maximum allowed value is 0.4).

DAYGM – Constant daily amount of melt which takes place at the snow-soil interface whenever there is a snow cover (mm•day-1).

VARIABLES DECLARED

`WE` – Water equivalent of ice portion of snow cover (mm).

`NEGHS` – Heat deficit (mm).

`LIQW` – Liquid water held by the snow (mm).

`TINDEX` – Antecedent temperature index (°C).

`ACCMAX` – Maximum amount of water equivalent that existed during accumulation period (mm).

`SB` – Water equivalent when new snowfall first occurs on a partly bare area (mm).

`SBAESC` – Areal cover when new snowfall occurs on a partly bare area (decimal fraction).

`SBWS` – Water equivalent where the areal cover drops below 100% when melt occurs after new snowfall takes place on a partially bare area (mm).

`STORGE` – Lagged excess liquid water in storage (mm).

`AEADJ` – Areal index value computed for use in depletion curve computations after an adjustment to the areal extent of snow cover (mm).

`EXLAG(7)` – Average hourly lagged excess water for each precipitation time interval (mm).

`SNDPT` – Snow depth (cm).

`SNTMP` – Snow cover temperature (°C).

EXTERNAL VARIABLES USED

DESCRIPTION

This module does hourly snow accumulation and ablation.

REFERENCES

Anderson, E.A., 2006, Snow accumulation and ablation model – SNOW-17—Chap. II.2 of NOAA's NWS River Forecast System User Manual [online]: accessed November 18, 2008, at *http://www.weather.gov/oh/hrl//nwsrfs/users_manual/part2/_pdf/22snow17.pdf*.

DEVELOPER NAME AND ADDRESS

R. Steve Regan
U.S. Geological Survey
Box 25046, MS 412
Denver Federal Center
Lakewood, CO 80225

For more information concerning this publication contact:
Director
USGS Pennsylvania Water Science Center
215 Limekiln Road
New Cumberland, Pennsylvania 17070
dc_pa@usgs.gov

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