Simulation of the Quantity, Variability, and Timing of Streamflow in the Dennys River Basin, Maine, by Use of a Precipitation-Runoff Watershed Model

By Robert W. Dudley

Prepared in cooperation with the
Maine Department of Marine Resources
Bureau of Sea Run Fisheries and Habitat

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Conversion Factors and Datums

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	0.4047	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
acre-inch (acre-in.)	102.79	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)

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 (NAVD 83).

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

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Abstract

The U.S. Geological Survey (USGS), in cooperation with the Maine Department of Marine Resources Bureau of Sea Run Fisheries and Habitat, began a study in 2004 to characterize the quantity, variability, and timing of streamflow in the Dennys River. The study included a synoptic summary of historical streamflow data at a long-term streamflow gage, collecting data from an additional four short-term streamflow gages, and the development and evaluation of a distributed-parameter watershed model for the Dennys River Basin. The watershed model used in this investigation was the USGS Precipitation-Runoff Modeling System (PRMS).

The Geographic Information System (GIS) Weasel was used to delineate the Dennys River Basin and subbasins and derive parameters for their physical geographic features. Calibration of the models used in this investigation involved a four-step procedure in which model output was evaluated against four calibration data sets using computed objective functions for solar radiation, potential evapotranspiration, annual and seasonal water budgets, and daily streamflows. The calibration procedure involved thousands of model runs and was carried out using the USGS software application Luca (**L**et **u**s **c**alibrate). Luca uses the Shuffled Complex Evolution (SCE) global search algorithm to calibrate the model parameters. The SCE method reliably produces satisfactory solutions for large, complex optimization problems. The primary calibration effort went into the Dennys main stem watershed model. Calibrated parameter values obtained for the Dennys main stem model were transferred to the Cathance Stream model, and a similar four-step SCE calibration procedure was performed; this effort was undertaken to determine the potential to transfer modeling information to a nearby basin in the same region. The calibrated Dennys main stem watershed model performed with Nash-Sutcliffe efficiency (NSE) statistic values for the calibration period and evaluation period of 0.79 and 0.76, respectively. The Cathance Stream model had an NSE value of 0.68.

The Dennys River Basin models make use of limited streamflow-gaging station data and provide information to characterize subbasin hydrology. The calibrated PRMS watershed models of the Dennys River Basin provide simulated daily streamflow time series from October 1, 1985, through September 30, 2006, for nearly any location within the basin. These models enable natural-resources managers to characterize the timing and quantity of water moving through the basin to support many endeavors including geochemical calculations, water-use assessment, Atlantic salmon population dynamics and migration modeling, habitat modeling and assessment, and other resource-management scenario evaluations. Characterizing streamflow contributions from subbasins in the basin and the relative amounts of surface- and ground-water contributions to streamflow throughout the basin will lead to a better understanding of water quantity and quality in the basin. Improved water-resources information will support Atlantic salmon protection efforts.

Introduction

The Dennys River is an important habitat for wild Atlantic salmon. Currently, wild Atlantic salmon populations are protected under the U.S. Endangered Species Act and are the subject of a comprehensive recovery program. In 1997, the State of Maine developed a conservation plan for Atlantic salmon in seven rivers in Maine, which include the Dennys River (Maine Atlantic Salmon Task Force, 1997). As part of its implementation, the plan called for the development of water-management plans for each of the river basins. The U.S. Geological Survey (USGS), in cooperation with the Maine Department of Marine Resources Bureau of Sea Run Fisheries and Habitat (MBSRFH), began a study in 2004 to characterize the quantity, variability, and timing of streamflow in the Dennys River. The study included a synoptic summary of historical streamflow data at a long-term streamflow gage (Dudley, 2005), collecting data from an additional four short-term streamflow gages, and the development and evaluation of a distributed-parameter watershed model.

The watershed modeling work for the Dennys River Basin directly or indirectly supports tasks of developing water-use management plans for Distinct-Population Segment (DPS) rivers, assessments of irrigation impacts on hydrology and Atlantic salmon, strategic planning and development of comprehensive flow monitoring in DPS basins, assessment of the potential for ground-water withdrawals to impact streamflow and cold water discharges, and determination of the cumulative effects of current and proposed irrigation withdrawals on streamflows in Atlantic salmon watersheds.

Flow in streams in coastal Downeast Maine is maintained by a combination of ground-water inflow and surface runoff. The proportions are not consistent through time and depend on climate, precipitation events in the watershed, surficial geology, and land cover. Long-term streamflow data in the Dennys River Basin, collected at USGS streamflow-gaging station number 01021200 on the main stem of the Dennys River at Dennysville, can be used to assist with the management of water quantity and quality in the basin. The streamflow-gaging station has been in operation from October 1, 1955, through September 30, 1998, and from June 1, 2001, through the present (2008) (Stewart and others, 2006).

The timing and quantity of water moving through subwatersheds of the Dennys River Basin and the relative amounts of that water apportioned to surface runoff and ground-water discharge is not well known because ground-water and streamflow-gaging-station data are very limited. Using a watershed model to characterize streamflow contributions from subwatersheds in the basin and the relative amounts of surface- and ground-water contributions to streamflow throughout the watershed leads to a better understanding of water quantity and quality in the basin; this information will subsequently support the planning and execution of ongoing and future Atlantic salmon protection efforts.

Purpose and Scope

The purpose of this report is to document the characterization of hydrology of the Dennys River and its tributaries by use of a distributed-parameter watershed model. This report describes the construction, calibration, and evaluation of the watershed model. The model will provide supporting information for future Atlantic salmon protection and restoration efforts—such as data-network design, stream-chemistry calculations, salmon population modeling, and decision-making and scenario evaluation for flow management at Meddybemps Lake Dam within the Dennys River Basin.

Description of the Dennys River Basin

The Dennys River Basin is in Washington County, eastern Maine, on the coast of the Atlantic Ocean (fig. 1). Draining an area of 132 mi^2, the main stem of the Dennys River flows about 20 mi from Meddybemps Lake in the northwestern part of the basin to Cobscook Bay on the Atlantic Ocean in the southeastern part of the basin (Fontaine, 1982). The headwaters at Pleasant Lake have an approximate water-surface elevation of 230 ft. The largest tributary to the Dennys River is Cathance Stream (drainage area 35.4 mi^2), which joins the Dennys River about 1 mi upstream from the mouth at Cobscook Bay (Fontaine, 1982). The USGS streamflow-gaging station on the main stem of the Dennys River at Dennysville (01021200) is upstream from the confluence of Cathance Stream and gages runoff from a 92.9-mi^2 drainage area; of that, runoff from 44.7 mi^2 (48 percent) is controlled at the outlet of Meddybemps Lake (fig. 1).

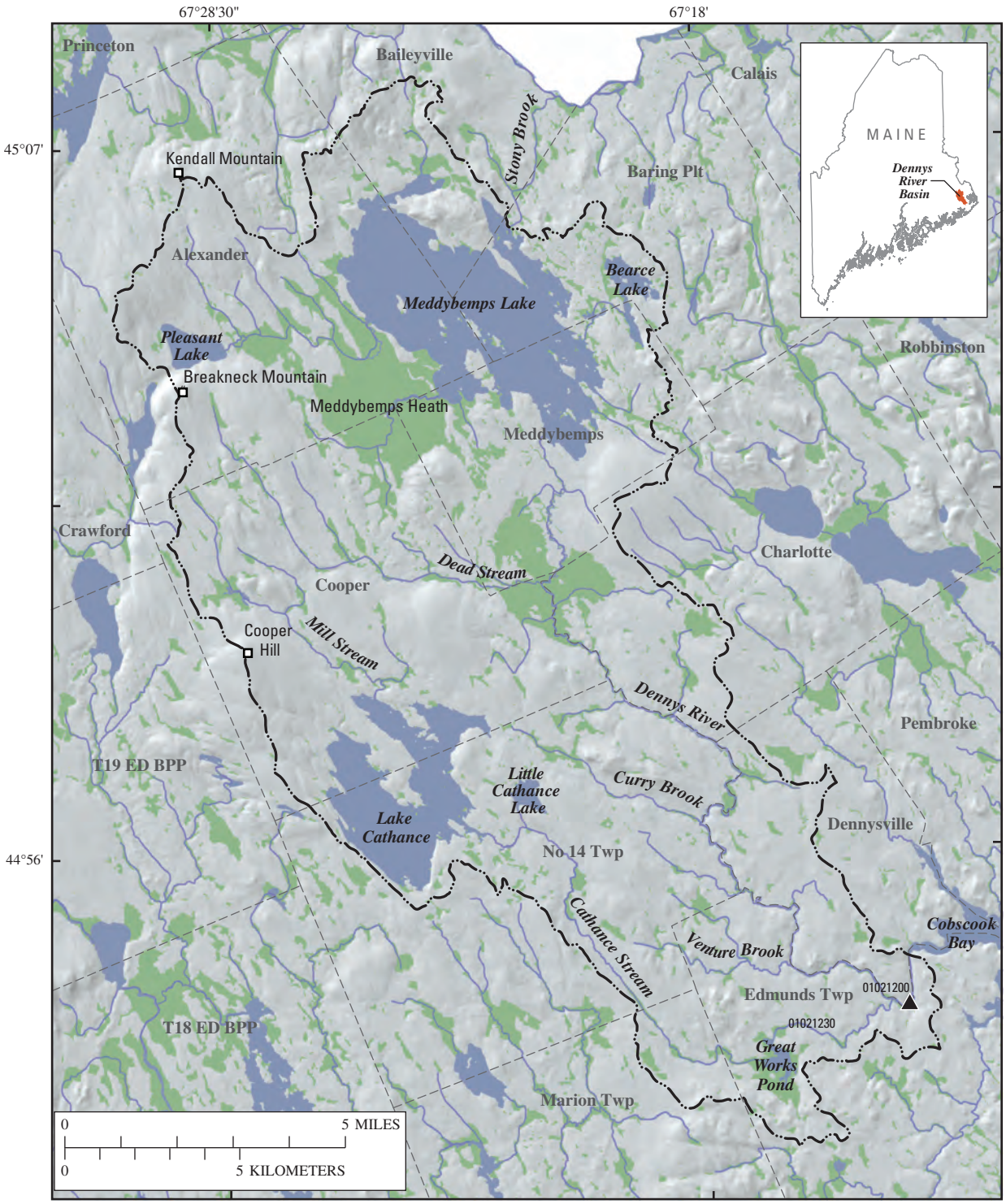
The Dennys River Basin is characterized by rolling topography with little development. The topography around Meddybemps Lake and the headwaters of Cathance Stream is hilly with altitudes of about 590 ft at Kendall Mountain, 660 ft at Breakneck Mountain, and 710 ft at Cooper Hill along the northwestern watershed boundary (fig. 1). The lowest altitude in the basin is sea level at the mouth of the Dennys River. The watershed is rural and is predominantly forested with wetlands, lakes, and ponds, some blueberry agriculture fields, clear cuts, partial cuts, regenerating forest, and light residential development.

Surficial Geology

The basin lies in a hydrophysiographic region of broad lowlands that were inundated by the ocean during deglaciation approximately 14,000 to 12,500 years ago (Dorion and others, 2001; Randall, 2000). Consequently, most surficial geologic materials in the basin are glacial till, and the remainder of the materials are composed of fine-grained glaciomarine deposits (typically silt, clay, and sand); swamp, marsh, and bog deposits (typically peat, muck, clay, silt, and sand); and eskers (typically gravel and sand) (Thompson and Borns, 1985). Fine-grained glaciomarine deposits (silt, clay, and sand) are characteristic of the main-channel corridor and the wetlands south and southwest of Meddybemps Lake.

Climate

The climate of the Dennys River Basin is temperate, with mild summers and cold winters. The mean annual air temperature from 1971 to 2000 was about 44°F, with mean monthly air temperatures ranging from about 20°F in January to about 66°F in July (National Oceanic and Atmospheric Administration, 2002). Mean annual precipitation during the same 30-year period was approximately 45 in., which was fairly evenly distributed throughout the year (National Oceanic and Atmospheric Administration, 2002). Mean annual evapotranspiration (loss of water to the atmosphere by evaporation from the soil and transpiration from plants) from 1951 through 1980 was about 18 in. (Randall, 1996). Measured mean annual runoff from 1955 through 2005 was about 28 in. (Stewart and others, 2006).



Base from USGS and Maine Office of GIS digital files,
NAD 83, Universal Transverse Mercator projection, Zone 19

EXPLANATION

Wetlands — Basin boundary — Geographic location — 01021200 Streamflow-gaging station and identifier

Figure 1. The Dennys River Basin, Washington County, Maine.

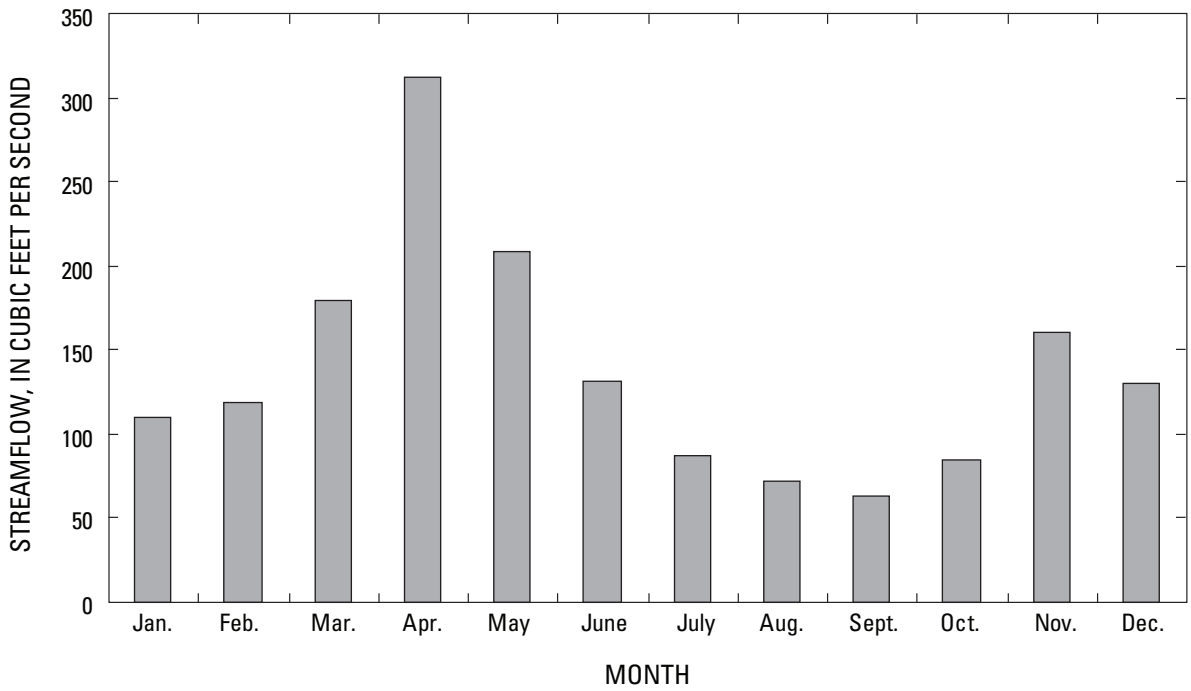


Figure 2. Median monthly streamflows measured at USGS streamflow-gaging station number 01021200 on the Dennys River at Dennysville, Maine (median monthly statistics were computed on the basis of the period of record from October 1, 1985, through September 30, 1998, and from June 1, 2001, through September 30, 2006).

Streamflow

Median monthly streamflows in the Dennys River, recorded at USGS streamflow-gaging station number 01021200 at Dennysville, show a seasonal variation that is common in Maine (fig. 2). The largest streamflows in coastal Maine typically occur in the spring (March, April, and May), when rain falls on a dense (ripe) snowpack or on saturated soils. Streamflows then recede as snowmelt ends and evapotranspiration increases. The recession of streamflow typically persists into late summer (August and September) because of high evapotranspiration. Streamflow in late summer is dominated by ground-water discharge and is frequently augmented by runoff from rainfall events. As evapotranspiration decreases in the fall (October and November), streamflow increases. Repeated rainfall events and the occasional contribution of tropical-system-related precipitation can result in high streamflows during the fall. Low streamflows can occur during the winter (December, January, and February) if precipitation and surface water are frozen for extended periods of time.

Much of the streamflow in the Dennys River is regulated by Meddybemps Lake Dam, 14 mi upstream from the USGS gage at Dennysville. The usable capacity of Meddybemps Lake is estimated to be 1.507 billion ft^3 (Stewart and others, 2006). The operating objectives of the dam changed with the transfer of ownership to the MBSRFH in 1973. Prior to 1973, the dam was used for power generation. At present (2008), the MBSRFH regulates outflow from Meddybemps Lake to maximize favorable habitat conditions for resident and migratory life stages of Atlantic salmon, particularly during low-streamflow periods. In general, usable storage in Meddybemps Lake is raised from April to June by capturing spring runoff, lowered from July to October to augment low streamflows, and held constant from November to March (Kleinschmidt Energy and Water Resource Consultants, 2002). There are no known consumptive uses of any water body in the Dennys River Basin (Arter, 2005).

Methods of Study

The following sections of the report document the data used for analyses, limitations of those data, and the analyses performed, including a description of the watershed model used and its input requirements.

Data Collection

Streamflow data were collected by the USGS using techniques described by Rantz and others (1982). Streamflow data have been continuously collected (15-minute intervals) at streamflow-gaging station 01021200 on the Dennys River at Dennysville from October 1, 1955, through September 30, 1998, and from June 1, 2001, through the present (2008). Data also have been collected at streamflow-gaging station 01021230 on the Cathance Stream at Edmunds from May 20, 2004, through September 30, 2006 (fig. 3, table 1).

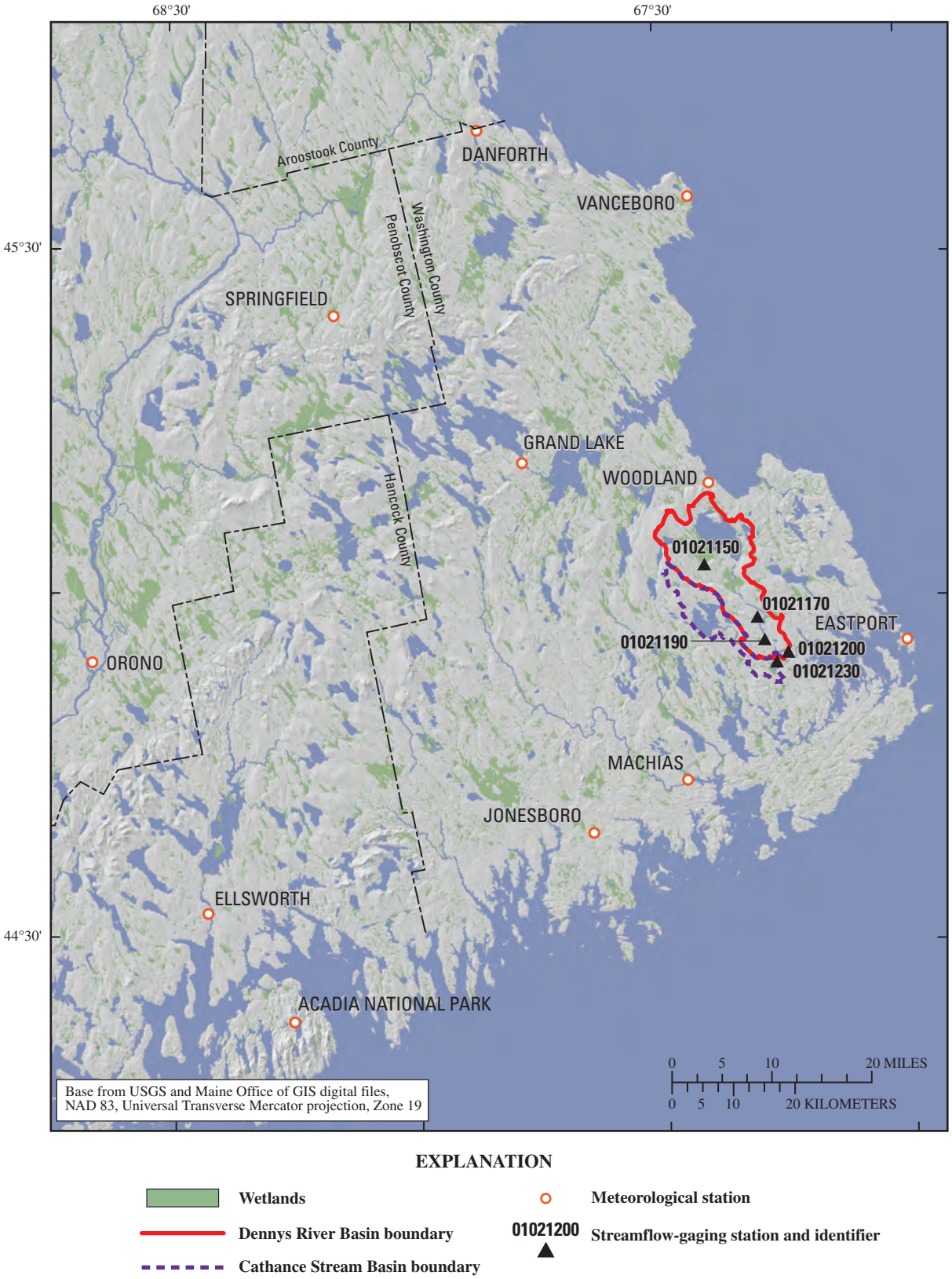


Figure 3. Hydrologic and meteorological data network used in this investigation.

Continuous streamflow data also were retrieved from the National Water Information System (NWIS) (Hoopes, 2004; Sauer, 2002).

Occasional low-flow measurements and approximately weekly stage readings were made at partial-record streamflow-gaging stations 01021150 on Dead Stream at Cooper, 01021170 on Curry Brook near Dennysville, and 01021190 on Venture Brook near Dennysville (fig. 3, table 1). Streamflows were computed from the stage readings for these three partial-record stations from July 1 through October 31, 2004, and from June 12 through November 13, 2005. Streamflow data were not computed for station 01021150 on Dead Stream during 2004 because the presence of excessive aquatic vegetation affected the quality of the data.

The Meddybemps Lake Dam outflow ratings, historical dam gate settings, and Meddybemps Lake water-level observations were provided to USGS (Michael Loughlin, Maine Department of Marine Resources Bureau of Sea Run Fisheries and Habitat, written communs., 2005, 2006, 2007). The outflow ratings provide outflow estimates from the dam, canal weir, and fishways as a function of lake level and gate settings—thus, using the rating, an outflow can be estimated for a known lake level and gate opening setting. For the period of record from 1974 through 2006, the MBSRFH measured and recorded lake levels and gate settings approximately every 2 weeks. Overspill at the dam, canal weir, and fishways during very high water was estimated using structure geometry measurements and basic broad-crested weir hydraulic approximations.

Other than the dam, weir, and fishways at the southern end of Meddybemps Lake, Stony Brook provides the capacity for a small amount of outflow from the lake. A 600-ft-long rock wall at the northern perimeter of Meddybemps Lake prevents most outflow to Stony Brook (Kleinschmidt Energy and Water Resource Consultants, 2002); however, during periods of high-water conditions, a small amount of water drains from the lake via Stony Brook. Water flowing out of the lake through Stony Brook crosses the watershed boundary and empties into the St. Croix River. A rating for estimating outflows through Stony Brook during high-water conditions was provided to USGS (Michael Loughlin, Maine Department of Marine Resources Bureau of Sea Run Fisheries and Habitat, written communs., 2005, 2006, 2007).

Daily precipitation data have been collected at the USGS precipitation gage 445404067145201, co-located with streamflow-gaging station 01021200 at Dennysville, from May 22, 2004, through present (2008). Precipitation data were retrieved from NWIS (Hoopes, 2004; Sauer, 2002). In addition to daily precipitation data collected at the USGS precipitation gage, data also were used from National Weather Service (NWS) meteorological stations near the towns of Danforth, Vanceboro, Springfield, Grand Lake, Woodland, Orono, Eastport, Machias, Jonesboro, and Ellsworth, and in Acadia National Park (fig. 3, table 2). Precipitation data collected at the basin outlet (station 445404067145201) were used to assure the quality of the NWS data and to fill in missing NWS observations (from May 22, 2004, through September 30, 2006). Daily minimum and maximum air temperature data also were collected at the same 11 NWS meteorological stations cited above for precipitation data. Both precipitation and temperature data were retrieved from the National Climatic Data Center.

A 1:24,000-scale USGS digital elevation model (DEM) of the Dennys River Basin was used to describe physical attributes of the basin. The 100-ft DEM is a geographic information system (GIS) data set containing a spatial grid of data, 100 ft on center, with altitude reported at each grid point. DEM data were downloaded from the USGS National Map Seamless Server (U.S. Geological Survey, 2005).

Additional physical attributes of the basin were described using soil, land cover, and forest speciation and density data. The U.S. General Soil Map (STATSGO; U.S. Department of Agriculture, 1994) delineates general soil units and was derived by the National Cooperative Soil Survey using 1:250,000-scale topographic quadrangles. STATSGO was used in this investigation to broadly describe surficial soils

Table 1. U.S. Geological Survey streamflow-gaging stations used in this investigation, Dennys River Basin, Maine.

[Latitude and longitude in degrees, minutes, and seconds]

U.S. Geological Survey streamflow-gaging station		Latitude (north)	Longitude (west)	Drainage area (square miles)	Record type	Period of record used in this investigation
Number	Name					
01021150	Dead Stream at Cooper	45°00'19"	67°24'59"	6.51	Partial	2005
01021170	Curry Brook near Dennysville	44°56'25"	67°18'14"	3.65	Partial	2004–05
01021190	Venture Brook near Dennysville	44°54'14"	67°17'15"	3.13	Partial	2004–05
01021200	Dennys River at Dennysville	44°54'05"	67°14'51"	92.9	Continuous	1980–98, 2001–06
01021230	Cathance Stream at Edmunds	44°53'13"	67°16'01"	32.7	Continuous	2004–06

Table 2. Meteorological stations used in this investigation in the vicinity of Dennys River Basin, Maine.

[Latitude and longitude in degrees and minutes; USGS, U.S. Geological Survey; NWS, National Weather Service]

Meteorological station		Latitude (north)	Longitude (west)	Altitude (feet)	Agency	Period of record used in this investigation
Number	Location					
445404067145201	Dennysville	44°54'	67°15'	72	USGS	2004–06
171833	Danforth	45°40'	67°52'	380	NWS	1988–2006
178974	Vanceboro	45°34'	67°26'	420	NWS	1980–2006
178353	Springfield	45°24'	68°10'	440	NWS	1980–98
173261	Grand Lake	45°11'	67°47'	290	NWS	1980–2006
179891	Woodland	45°09'	67°24'	140	NWS	1980–2006
176430	Orono	44°54'	68°40'	115	NWS	1980–2001, 2003–06
172426	Eastport	44°55'	67°00'	85	NWS	1980–2004, 2006
174878	Machias	44°43'	67°27'	20	NWS	1980–81
174183	Jonesboro	44°39'	67°39'	185	NWS	1980–2006
172620	Ellsworth	44°32'	68°26'	20	NWS	1980–95
170100	Acadia National Park	44°21'	68°16'	470	NWS	1982–2006

and soil profile properties in the basin. Quality assurance and refinements of soil characteristics were made using a surficial geologic map of Maine (Thompson and Borns, 1985).

Land-cover types were characterized using version 2.0 of the North American Land Cover Characteristics Data Base (NALCC). The NALCC land-cover data were derived by the USGS in cooperation with the University of Nebraska and the European Commission's Joint Research Centre from satellite imagery collected during 1992–93 (Loveland and others, 1991). These data were used to broadly classify land-cover types in the basin. Quality assurance and refinement of land-cover types were achieved using a digital land-cover data set for the State of Maine derived from satellite imagery from the years 1999–2001 and panchromatic imagery from 2004. The Maine Land-Cover Data Set (MELCD) is published by the Maine Office of Geographic Information Systems (MEGIS) and can be accessed online at http://megis.maine.gov/catalog/ (accessed June 21, 2006).

The U.S. Forest Type Groups and U.S. Forest Density maps were used to broadly characterize dominant forest speciation and vegetation density in the basin. Both data sets are published by the U.S. Forest Service (Zhu and Evans, 1994; Zhu, 1994). Quality-assurance efforts and refinements to forest types were made using the MELCD.

Precipitation-Runoff Watershed Model

In general, precipitation-runoff models simulate the generation of runoff from a basin when rain and meltwater reach the surface of the ground. The models use various algorithms and methods of approximation to describe the physical processes that affect the movement of water over and through the soil. Runoff processes simulated by a precipitation-runoff model may include overland flow, shallow subsurface flow, and ground-water flow. Typical input to a precipitation-runoff model may include precipitation, air temperature, solar radiation, wind, and parameters describing the physical characteristics of the basin including slope, aspect, elevation, and soil types. Typical output from a precipitation-runoff model is a time-series graph of the rate of runoff for a point of interest on a hillside or in a channel called a hydrograph. Output hydrographs represent the integrated hydrologic response of the entire basin to precipitation input on the basis of a basin's climatic, hydrologic, and physical characteristics.

The USGS's Precipitation-Runoff Modeling System (PRMS; Leavesley and others, 1983) was used in this investigation to simulate daily flows for the Dennys River Basin. PRMS is well-suited for modeling runoff from rural basins and has been applied to many basins

in the U.S. including the Willamette River Basin, Oregon (Laenen and Risley, 1997); Methow River Basin, Washington (Ely and Risley, 2001; Ely 2003); Yakima River Basin, Washington (Mastin and Vaccaro, 2002); Feather River Basin, California (Koczot and others, 2004); Yampa River Basin Colorado (Parker and Norris, 1989); Ah-Shi-Sle-Pah Wash Basin, New Mexico (Hejl, 1989); Lake Tahoe and Truckee River Basins, California and Nevada (Jeton, 1999a, b); Williams Draw and Bush Draw Basins, Colorado (Kuhn, 1989); Tug Fork Basin of Kentucky, Virginia, and West Virginia (Scott, 1984); 10 basins in Vermont (Olson, 2002); and Bald Mountain and Bishop Mountain Brook Basins, Maine (Fontaine, 1987).

PRMS is a deterministic, distributed-parameter modeling system. The model is deterministic in that it computationally incorporates multiple components of the hydrologic cycle as understood through known physical laws or empirical relations in hydrologic science. The modeled hydrologic relations are typically governed by quantifiable physical characteristics of the basin. Parameters describing the physical basin characteristics are assigned in a distributed fashion, representing the spatial variation (heterogeneity) in basin characteristics. In this manner, the deterministic, distributed-parameter model is designed to simulate the hydrologic system as realistically as possible.

Parameters describing the physical basin characteristics are distributed among subbasin units referred to as Modeling Response Units (MRUs). The size of an MRU is determined on the basis of spatial variation of physical characteristics across the basin; MRUs are intended to encompass subbasins with approximately homogeneous basin characteristics such as slope, aspect, soil type, vegetation type, etc. A lake or wetland is commonly represented by a single MRU because of its homogeneous characteristics, for example. Other subbasin units may be represented by one, two, or more MRUs depending on the degree of variability in topography, soils, and other basin characteristics.

The following paragraphs from Leavesley and others (1983, p. 7–9) provide a good summary of the operational design of PRMS (fig. 4).

> System inputs are precipitation, air temperature, and solar radiation. Precipitation in the form of rain, snow, or a mixture of both is reduced by interception and becomes net precipitation delivered to the watershed surface. The energy inputs of temperature and solar radiation drive the processes of evaporation, transpiration, sublimation, and snowmelt. The watershed system is conceptualized as a series of reservoirs whose outputs combine to produce the total system response.
>
> The impervious-zone reservoir represents an area with no infiltration capacity. The reservoir has a maximum retention storage capacity which must be satisfied before surface runoff will occur. Retention storage is depleted by evaporation when the area is snow free.
>
> The soil-zone reservoir represents that part of the soil mantle that can lose water through the processes of evaporation and transpiration. Average rooting depth of the predominant vegetation covering the soil surface defines the depth of this zone. Water storage in the soil zone is increased by infiltration of rainfall and snowmelt and depleted by evapotranspiration. Maximum retention storage occurs at field capacity; minimum storage (assumed to be zero) occurs at wilting point. The soil zone is treated as a two-layered system. The upper layer is termed the recharge zone and is user-defined as to depth and water-storage characteristics. Losses from the recharge zone are assumed to occur from evaporation and transpiration; losses from the lower zone occur only through transpiration.
>
> The computation of infiltration into the soil zone is dependent on whether the input source is rain or snowmelt. All snowmelt is assumed to infiltrate until field capacity is reached. At field capacity, any additional snowmelt is apportioned between infiltration and surface runoff. At field capacity, the soil zone is assumed to have a maximum daily snowmelt infiltration capacity. All snowmelt in excess of this capacity contributes to surface runoff. Infiltration in excess of field capacity first is used to satisfy recharge to the ground-water reservoir, having a maximum daily limit. Excess infiltration, above this limit, becomes recharge to the subsurface reservoir. Water available for infiltration as the result of a rain-on-snow event is treated as snowmelt if the snowpack is not depleted and as rainfall if the snowpack is depleted.
>
> For rainfall with no snowcover, the volume infiltrating the soil zone is computed as a function of soil characteristics, antecedent soil-moisture conditions, and storm size. For daily-flow computations, the volume of rain that becomes surface runoff is computed using a contributing-area concept. Daily infiltration is computed as net precipitation less surface runoff. For stormflow-hydrograph generation, infiltration is computed using a form of the Green and Ampt equation (Philip, 1954). Surface runoff for these events is net precipitation less computed infiltration. Infiltration in excess of field capacity is treated the same as daily infiltration.
>
> The subsurface reservoir performs the routing of soil-water excess that percolates to shallow ground-water zones near stream channels or that moves downslope from point of infiltration to some point of discharge above the water table. Subsurface flow is considered to be water in the saturated-unsaturated

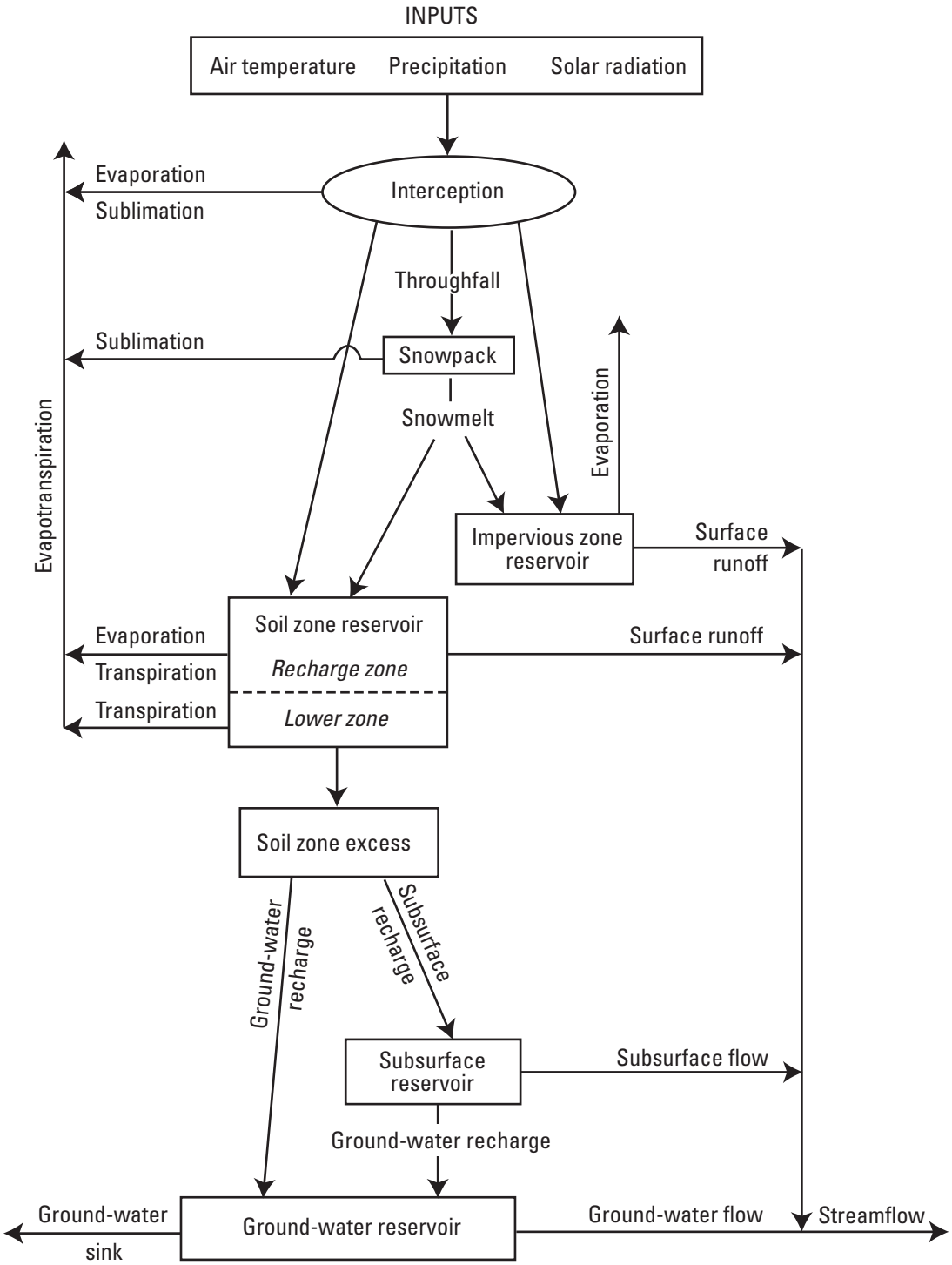


Figure 4. Schematic diagram showing the operational design of the Precipitation Runoff Modeling System (PRMS; modified from Leavesley, and others, 1983, fig. 2).

and ground-water zones that is available for relatively rapid movement to a channel system. The subsurface reservoir can be defined either as linear or nonlinear.

Recharge to the ground-water reservoir can occur from the soil zone and the subsurface reservoir. Soil zone recharge has a daily upper limit and occurs only when field capacity is exceeded in the soil zone. Subsurface reservoir recharge is computed daily as a function of a recharge rate coefficient and the volume of water stored in the subsurface reservoir. The ground-water reservoir is a linear reservoir and is the source of all baseflow. Movement of water through the ground-water system is computed as a function of storage in the ground-water reservoir.

Streamflow is the sum of direct surface runoff, subsurface flow, and baseflow from each HRU.

The Modular Modeling System (MMS), developed by Leavesley and others (1996), is a software application that provides a framework for developing and integrating algorithms for physical-process models. Process-specific algorithms are stored in MMS in a module library where they are used to construct models that simulate a variety of water, energy, and biogeochemical processes. This modular approach to modeling enables users to construct custom models using existing modules or develop custom modules for specific applications.

MMS was used in this investigation to construct and run PRMS watershed models for the Dennys River Basin. A new PRMS module also was developed for this investigation. As much of the streamflow in the Dennys River is regulated by Meddybemps Lake Dam, an important objective of this investigation was to model regulated and unregulated outflow from surface reservoirs (lakes) as realistically as possible. The resulting "lakes" module computationally accounts for lake inflows, storage (lake area and water-surface altitude), ground-water seepage, and outflows by either a broad-crested weir hydraulic approximation (natural outflow) or a user-defined outflow rating as a function of gate opening and lake water-surface elevation (appendix A).

Basin Characterization for Watershed Modeling

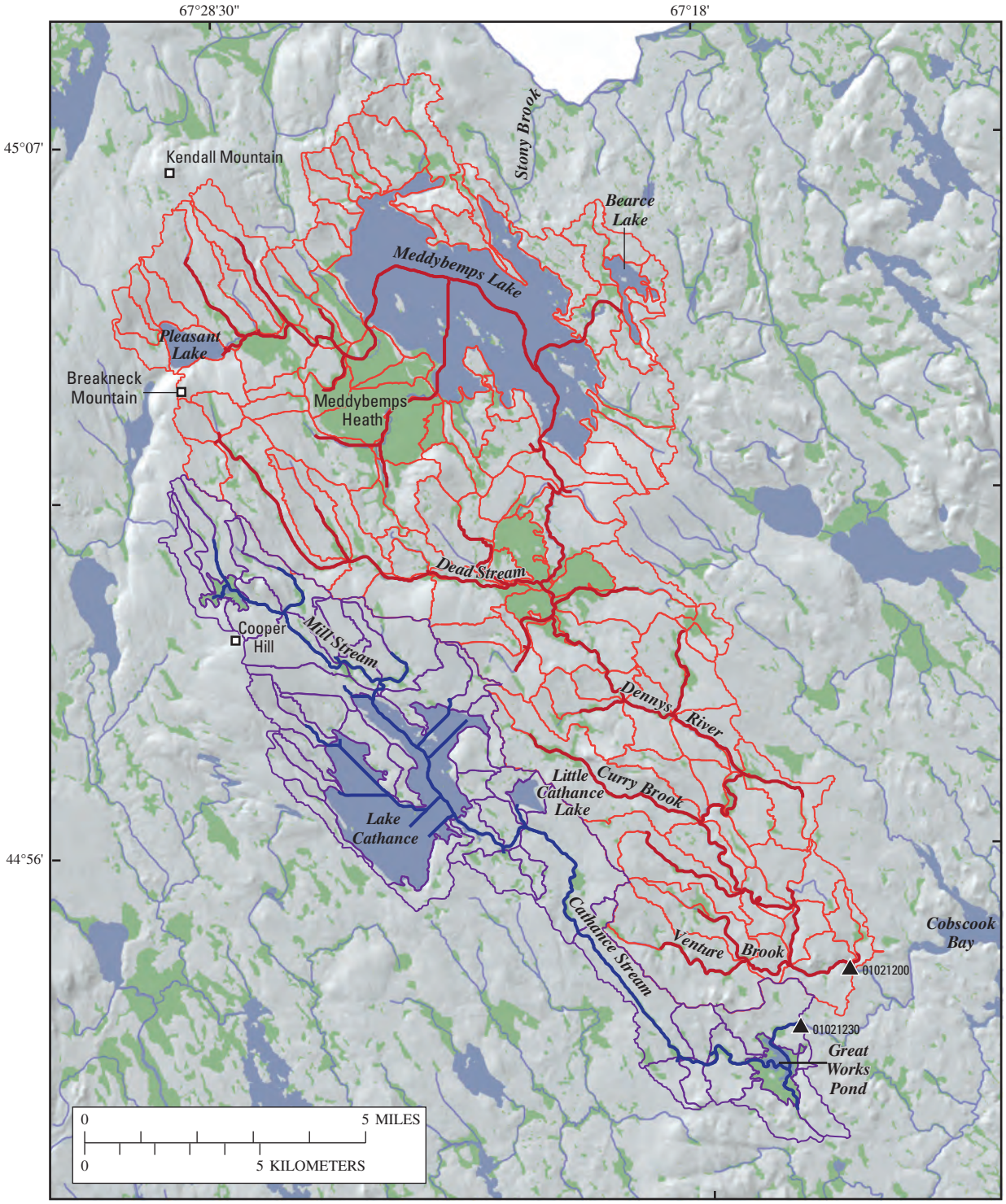
MMS works in conjunction with a GIS interface called the GIS Weasel (Viger and Leavesley, 2006). The GIS Weasel provides a suite of tools to help prepare spatial information, lumped or distributed, for input to watershed or other environmental models. Using this set of tools provides objective and reproducible methods for generating model input parameters. In this investigation, the GIS Weasel was used to delineate the basin, subdivide it into MRUs, and characterize its physical features into the requisite sets of parameters for input to PRMS.

The GIS Weasel requires as input a DEM of the basin to be modeled. Using the DEM, the GIS Weasel generates a flow-direction surface and, in turn, derives a flow-accumulation surface. Each point on the flow-accumulation surface states the upstream drainage area. A drainage network is extracted from this surface by finding all points where the flow accumulation is equal to or greater than a user-specified threshold (Viger and Leavesley, 2006).

In this investigation, a threshold of 0.6 mi^2 was used. This threshold value generated a stream network of suitable density. Using the flow-direction surface, the GIS Weasel delineates basin boundaries on the basis of a user-specified pour point, or basin outlet. Two basins within the Dennys River Basin were delineated in this fashion. The two pour points were identified as the locations of the USGS streamflow-gaging stations on the Dennys River at Dennysville (station number 01021200) and on Cathance Stream at Edmunds (01021230). The GIS Weasel delineations yielded drainage areas within 0.9 percent of the published drainage areas (Fontaine, 1982) for the two basins.

Next, the GIS Weasel was used to derive MRUs for each basin. Initial MRUs were defined by determining the contributing area associated with each link in the drainage network and splitting these areas with the same drainage network into "left-bank" and "right-bank" units. Additional MRUs were formed on the basis of specific geologic or hydrologic features including significant sand and gravel deposits, wetlands (such as Meddybemps Heath), and water bodies (such as Meddybemps Lake, Lake Cathance, Pleasant Lake, Bearce Lake, and Little Cathance Lake) for which specific model parameters would later be set to describe their unique hydrologic properties. Finally, MRUs smaller than 0.2 mi^2 were dissolved into neighboring MRUs. The process resulted in the delineation of 128 MRUs for the 01021200 (Dennys main stem) basin and 54 MRUs for the 01021230 (Cathance Stream) basin (fig. 5). MRUs in the 01021200 basin ranged in size from 0.2 to 11.4 mi^2, with a mean MRU size of 0.7 mi^2. MRUs in the 01021230 basin ranged in size from 0.2 to 5.2 mi^2, with a mean MRU size of 0.6 mi^2.

The GIS Weasel was used to derive parameters for the physical geographic features of the Dennys River Basin using the U.S. General Soil Map, North American Land Cover Characteristics Data Base, U.S. Forest Type Groups, and U.S. Forest Density maps, and the DEM and its aforementioned derivative surfaces. Parameters derived for each MRU include: area, elevation, slope, aspect, vegetation type and density, precipitation-interception capacities, and soil types (table 3). During parameterization, the GIS Weasel also determined MRU-specific indices describing connectivity of MRUs with the drainage network and surface- and ground-water reservoirs. The MRU 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.



Base from USGS and Maine Office of GIS digital files,
NAD 83, Universal Transverse Mercator projection, Zone 19

EXPLANATION

Wetlands

Watershed model basin drainage network
Dennys River
Cathance Stream

Model response units (MRU)
Dennys River
Cathance Stream

Geographic location

01021200 **Streamflow-gaging station and identifier**

Figure 5. Model Response Units and drainage networks for the Dennys main stem and Cathance Stream watershed models.

Table 3. Sources of values for selected Modeling Response Unit (MRU) (distributed) and whole-model (non-distributed) Precipitation Runoff Modeling System (PRMS) parameters for the Dennys River Basin, Maine.

[GIS, derived from digital data sources using geographic information systems; Com., computed or estimated on the basis of climatological or hydrologic data or other related observations; Def., values as provided by Leavesley and others (1983); Cal., final value determined by way of calibration; MRU, modeling response unit; F, Fahrenheit; PET, potential evapotranspiration]

Parameter	Description	Source			
		GIS	Com	Def	Cal
	Distributed (MRU-dependent) parameters				
carea_max	Maximum area contributing to surface runoff (decimal fraction)				X
cov_type	Vegetation cover type	X			
covden_sum	Summer vegetation cover density (decimal fraction)	X			
covden_win	Winter vegetation cover density (decimal fraction)	X			
gwflow_coef	Ground-water routing coefficient; contribution to streamflow (in day^{-1})				X
gwsink_coeff	Ground-water sink coefficient (in day^{-1})				X
gwstor_init	Initial storage in each ground-water reservoir (in inches)				X
hru_area	MRU area (in acres)	X			
hru_aspect	MRU compass-bearing exposure (in degrees)	X			
hru_deplcrv	Index number for snowpack depletion curve			X	
hru_elev	MRU mean altitude (in feet)	X			
hru_gwres	Index of ground-water reservoir	X			
hru_percent_imperv	MRU percent impervious area (decimal fraction)	X			
hru_sfres	Index of surface reservoir	X			
hru_slope	MRU slope (vertical feet/horizontal feet; decimal fraction)	X			
hru_ssres	Index of subsurface reservoir	X			
hru_type	Index differentiating between land and lake/reservoir MRU types	X			
jh_coef_hru	MRU air temperature coefficient used in Jensen and Haise (1963) PET computations (in degrees F^{-1})		X		
rad_trncf	Transmission coefficient for short-wave radiation through the winter vegetation canopy (decimal fraction)		X		
smidx_coef	Coefficient in the nonlinear contributing area computations for surface runoff (decimal fraction)				X
smidx_exp	Exponent in contributing area computations for surface runoff (in $inches^{-1}$)				X
snarea_thresh	Maximum threshold water equivalent for application of the snow area depletion curve (in inches)	X			
snow_intcp	Snow interception storage capacity for major vegetation type on MRU (in inches)	X			
snowinfil_max	Maximum snow infiltration (in inches per day)			X	
soil_moist_init	Initial value for available water in the soil profile (in inches)	X			
soil_moist_max	Maximum water-holding capacity of the soil profile (in inches)				X
soil_rechr_init	Initial value for available water in the soil recharge zone (in inches)	X			
soil_rechr_max	Maximum value for available water in the soil recharge zone (in inches)				X
soil_type	Index indicating MRU soil type	X			

Table 3. Sources of values for selected Modeling Response Unit (MRU) (distributed) and whole-model (non-distributed) Precipitation Runoff Modeling System (PRMS) parameters for the Dennys River Basin, Maine.—Continued

[GIS, derived from digital data sources using geographic information systems; Com., computed or estimated on the basis of climatological or hydrologic data or other related observations; Def., values as provided by Leavesley and others (1983); Cal., final value determined by way of calibration; MRU, modeling response unit; F, Fahrenheit; PET, potential evapotranspiration]

Parameter	Description	Source			
		GIS	Com	Def	Cal
	Distributed (MRU-dependent) parameters—Continued				
soil2gw_max	Maximum value for soil water excess routed to ground water (in inches per day)				X
srain_intcp	Summer precipitation interception storage capacity for major vegetation type on MRU (in inches)	X			
ssr2gw_rate	Coefficient to route water from subsurface to ground water (in $days^{-1}$)				X
tmax_adj	MRU maximum temperature adjustment on the basis of slope and aspect of the MRU (in degrees F)	X			
tmin_adj	MRU minimum temperature adjustment on the basis of slope and aspect of the MRU (in degrees F)	X			
transp_beg	Month to begin summing MRU maximum temperatures; when sum is greater than or equal to transp_tmax, transpiration begins		X		
transp_end	Last month for transpiration computations		X		
transp_tmax	Temperature index to determine specific date of start of transpiration period (in degrees F)			X	
wrain_intcp	Winter rain interception storage capacity for major vegetation type on MRU (in inches)	X			
	Non-distributed (basinwide) parameters				
adjmix_rain	Monthly adjustment factor for the proportion of rain in a mixed rain/snow event (decimal fraction)				X
adjust_rain	Downscaling adjustment for rain (decimal fraction)				X
adjust_snow	Downscaling adjustment for snow (decimal fraction)				X
jh_coef	Monthly air temperature coefficient used in Jensen and Haise (1963) PET computations (in degrees F^{-1})				X
melt_force	Julian date to force snowpack to spring snowmelt stage			X	
melt_look	Julian date to begin looking for spring snowmelt			X	
tmax_allrain	Maximum temperature above which all precipitation is simulated as rain (in degrees F)				X
tmax_allsnow	Maximum temperature below which all precipitation is simulated as snow (in degrees F)				X

Calibration of the Precipitation-Runoff Watershed Model

Following model construction and initial parameterization with the GIS Weasel, the two watershed models were sequentially calibrated to determine the values of parameters that cannot be directly measured. Calibration used a step-wise, multiple-objective method. The Dennys main stem model was calibrated first because the gage at station 01021200 on the main stem had a longer historical record to calibrate to than the gage at station 01021230 on Cathance Stream. Following calibration of the Dennys main stem model, calibrated parameters (table 3) from that model were transferred to the Cathance Stream model which was, in turn, calibrated to its relatively short historical period of record. This calibration methodology provided a proof of concept for the transferability of calibrated watershed modeling information for use in modeling nearby basins. This methodology provided a means to calibrate parameters in a basin with a short historical record, with parameter values already close to their final values due to similar basin characteristics between adjacent basins.

The step-wise, multiple-objective calibration method used in this investigation followed a procedure similar to that of Hay and others (2006) in applying PRMS to the Yampa River Basin in Colorado. Calibration for the Dennys River Basin investigation involved a four-step procedure in which model output was evaluated against four independent data sets using computed objective functions. Objective functions are used to evaluate the fit between the simulated model output and measured values and serve as calibration criteria. During each step, selected model parameters were calibrated by improving one or more associated objective functions. The values of the previously calibrated parameters were carried forward into the next calibration step. The four-step procedure was repeated until no further improvement was made in the simulation.

The four steps with associated calibration data sets and objective functions were: (1) basin mean monthly solar radiation, with an objective function of the sum of the absolute difference in the logarithms of measured and simulated solar radiation; (2) basin mean potential evapotranspiration, with an objective function of the sum of the absolute difference in the logarithms of measured and simulated potential evapotranspiration; (3) annual and seasonal water balances, with multiple objective functions of the sums of the absolute value of the normalized residuals for each year and season; and (4) daily streamflows, with multiple objective functions of the normalized root mean square error for low flows, high flows, and all flows. In the case of this fourth calibration step, low flows were defined as any daily mean streamflow lower than 290 ft^3/s (85 ft^3/s), and high flows were defined as any daily mean hydrograph peak higher than 290 ft^3/s (85 ft^3/s) for the Dennys main stem (Cathance Stream) model.

The four-step calibration procedure described above involved thousands of model runs using the software application Luca (**L**et **u**s **c**alibrate) (Umemoto and others, 2006). Luca provides a user-friendly, systematic method for building and executing user-defined calibration procedures for any model constructed with MMS. Luca uses the Shuffled Complex Evolution (SCE) global search algorithm (Duan and others, 1994) to calibrate the model parameters; results of experimental studies indicated the SCE method reliably produced satisfactory solutions for large complex optimization problems (Duan and others, 1994). Luca was used by Hay and others (1996) to calibrate their PRMS model of the Yampa River Basin, Colorado, with satisfactory results.

Following SCE calibration of the Dennys main stem model using Luca, a limited, systematic approach of manual trial-and-error calibration was done with specific emphasis on matching simulated lake levels to measured lake levels for Meddybemps Lake while trying to preserve parameter values determined using the SCE approach. The Dennys main stem model was calibrated using 13 years of streamflow data collected from October 1, 1985, through September 30, 1998. Five years of streamflow record from October 1, 2001, through September 30, 2006, were used as an evaluation data set. When calibration of the Dennys main stem model was complete, the calibrated parameter set was transferred to the Cathance Stream model to provide a starting point for calibration. SCE calibration was done for the Cathance Stream model using the 2 available years of record (May 20, 2004, through September 30, 2006); due to the short period of record, a separate evaluation data set was not available for the Cathance Stream model.

The Nash-Sutcliffe efficiency (NSE) statistic (equation 1) was used as an overall measure of model performance; it is a normalized statistic that provides a measure of how well simulated output matches measured data (Moriasi and others, 2007; Nash and Sutcliffe, 1970):

$$NSE = \left[1 - \frac{\frac{1}{n}\sum_{i=1}^{n}\left(Q_{obs,i} - Q_{sim,i}\right)^2}{\frac{1}{n}\sum_{i=1}^{n}\left(Q_{obs,i} - \overline{Q}_{obs,i}\right)^2} \right], \qquad (1)$$

where

$Q_{obs,i}$ is the ith measurement for basin streamflow,
$Q_{sim,i}$ is the ith simulated basin streamflow,
$\overline{Q}_{obs,i}$ is the mean of the measured basin streamflow, and
n is the total number of measurements.

NSE ranges in value from negative infinity through 1.0; a value of 0.0 or less indicates that the mean measured streamflow is a better predictor than the simulated streamflows; and values between 0.0 and 1.0 are viewed as acceptable, with 1.0 indicating a perfect match between every measured and simulated streamflow.

Simulation of the Quantity, Variability, and Timing of Streamflow in the Dennys River Basin

This section of the report describes the results of the SCE calibration procedure for the Dennys main stem model only, as the greatest calibration effort went into this model. Calibrated parameter values obtained for the Dennys main stem model were transferred to the Cathance Stream model followed by a similar calibration procedure for the Cathance. The transfer and calibration of parameters for the Cathance Stream model was done to test the transferability of information gained by modeling a nearby basin. The Cathance Stream model performed well and supported the applicability of the transfer process.

Dennys Main Stem Model Calibration

The first step in the four-step Luca calibration procedure involved basin mean monthly solar radiation. The calibrated model yielded simulated solar radiation values nearly identical to the calibration data, which were interpolated from regression analysis of a nationwide climate network of Natural Resources Conservation Service snowpack telemetry stations and NWS climate stations (fig. 6; Hay and others, 2006). Evaluation values were reasonable, with variations from interpolated values being a function of the variability in meteorological input data for the short 6-year (2001–06) evaluation period.

The second step in the SCE calibration procedure involved basin mean monthly potential evapotranspiration (PET). Simulated potential evapotranspiration values were nearly identical to values calculated from PET maps produced by the NWS derived from the free water evaporation atlas of Farnsworth and others (1982) (fig. 7). Simulated values from the evaluation period were reasonable; modeled estimates of PET are computed with solar radiation following a procedure developed by Jensen and Haise (1963). Thus, the modeled PET results closely resemble those for solar radiation.

The third step in the SCE calibration procedure related simulated annual and seasonal water balances to basin runoff volumes measured at the downstream streamflow-gaging station (01021200). Seasonal runoff volumes were defined as total runoff for the following months associated with four seasons: winter—December, January, February; spring—March, April, May; summer—June, July, August; fall—September, October, November. Overall, there was good agreement between simulated and measured annual and seasonal runoff volumes. Total runoff for the 13-year calibration period was within -0.7 percent of measured runoff; simulated annual runoff totals ranged from -9.2 (water year[1] (WY) 1988) to 10.6 (WY 1986) percent of measured runoff, with 8 of the 13 years within 5 percent or better. Total runoff for the 5-year evaluation period was within 6.4 percent of measured runoff;

[1] The term "water year" denotes the 12-month period from October 1 to September 30 and is designated by the calendar year in which it ends and which includes 9 of the 12 months.

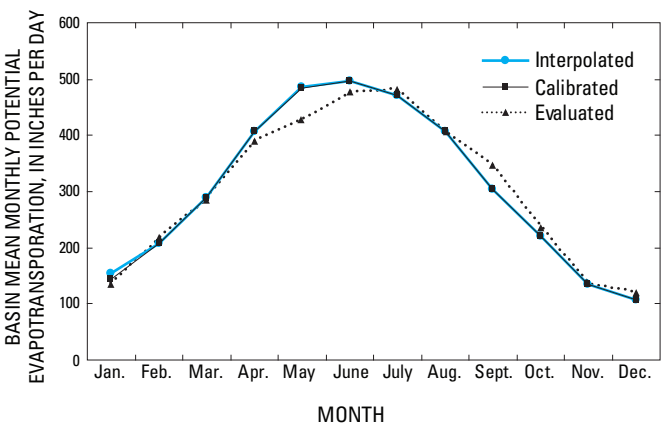


Figure 6. Interpolated data computed from regression analysis of nationwide climate network of Natural Resources Conservation Service snowpack telemetry stations and National Weather Service climate stations (calibrated model output for basin mean monthly solar radiation simulates the period from October 1, 1985, through September 30, 1998; evaluation model output simulates the period from October 1, 2001, through September 30, 2006).

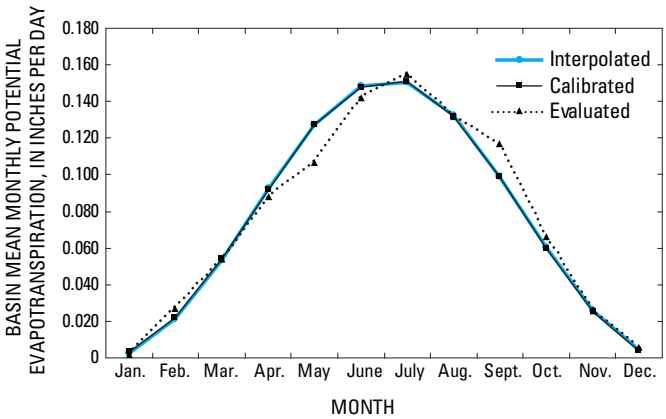


Figure 7. Interpolated data computed from potential evapotranspiration maps produced by the National Weather Service (calibrated model output for basin mean monthly potential evapotranspiration simulates the period from October 1, 1985, through September 30, 1998; evaluation model output simulates the period from October 1, 2001, through September 30, 2006).

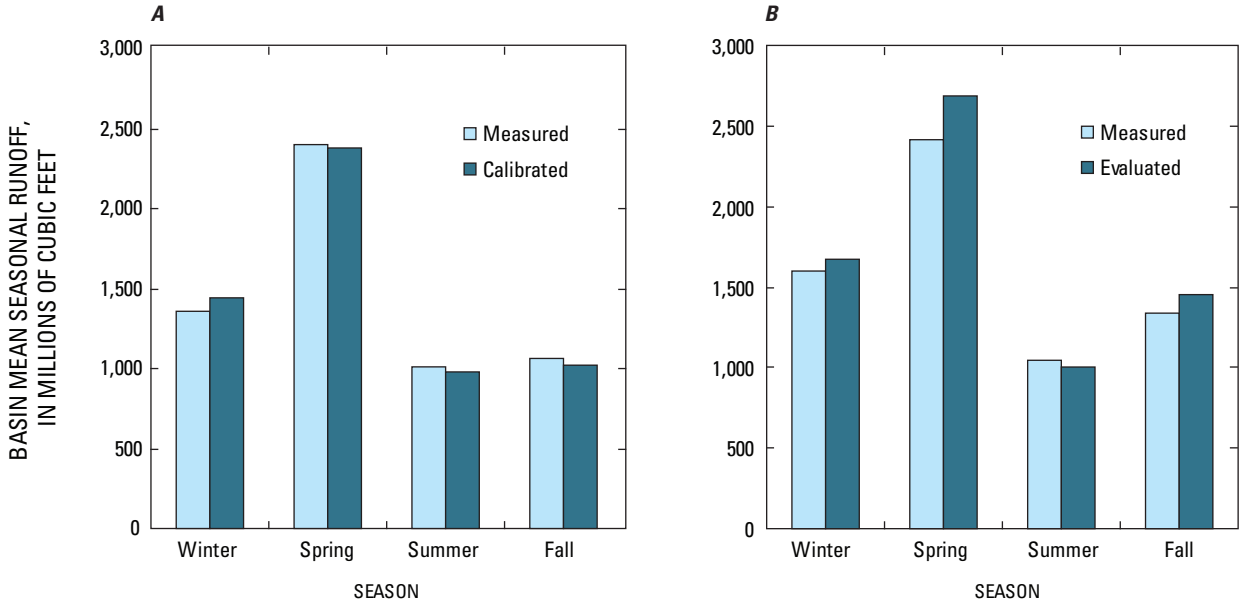


Figure 8. *(A)* Calibrated model output for basin mean seasonal outflow volumes simulating the period from October 1, 1985, through September 30, 1998; *(B)* evaluation model output simulating the period from October 1, 2001, through September 30, 2006. (Seasons are defined as: winter—December, January, February; spring—March, April, May; summer—June, July, August; fall—September, October, November.)

simulated annual runoff totals ranged from -10.2 (WY 2004) to 25.6 (WY 2005) percent of measured runoff, with 2 of the 5 years within 5 percent or better. Seasonal runoff volumes were within 5.9 percent or better for the calibration period and within 9.2 percent or better for the evaluation period.

The fourth step in the SCE calibration procedure related simulated daily streamflows to basin runoff measured at the downstream streamflow-gaging station (01021200). The objective of the calibration was to minimize differences between simulated and measured low flows, high flows, and the entire range of flows overall. In general, simulated flows matched measured flows reasonably well on a daily basis (fig. 9). High flows seem to have been underestimated by the model for the calibration period, and low flows seem to have been overestimated by the model for the evaluation period (fig. 9).

The final calibration step involved a limited, systematic approach of manual trial-and-error calibration, with specific emphasis on matching simulated to measured lake levels for Meddybemps Lake while trying to preserve parameter values determined using the four-step SCE calibration procedure. Overall, the model simulated Meddybemps Lake levels fairly well (fig. 10). It was important to calibrate lake levels accurately, as the lake level, in combination with the gate opening at Meddybemps Lake Dam, determines the outflow from Meddybemps Lake, which comprises a significant part of the overall streamflow in the basin.

NSE values for the calibration period and evaluation period were 0.79 and 0.76, respectively, indicating a satisfactory simulation in each case.

Cathance Stream Model Calibration

Calibrated parameter values obtained for the Dennys main stem model were transferred to the Cathance Stream model, and a similar four-step SCE calibration procedure was done for solar radiation, potential evapotranspiration, annual and seasonal water budgets, and daily streamflows. Although a very limited data set was available for calibration, the Cathance Stream model had an NSE value of 0.68 and demonstrated the potential to transfer PRMS parameter information from a nearby basin. There were not enough data to independently evaluate the Cathance Stream model. Numerical accuracy of the Cathance Stream and Dennys main stem models was very good with cumulative residual basin water balances of less than 0.04 in. over a 21-year simulation period (October 1, 1985, through September 30, 2006). The residuals (numerical error) are approximately five orders of magnitude less than the total amount of water input to the models.

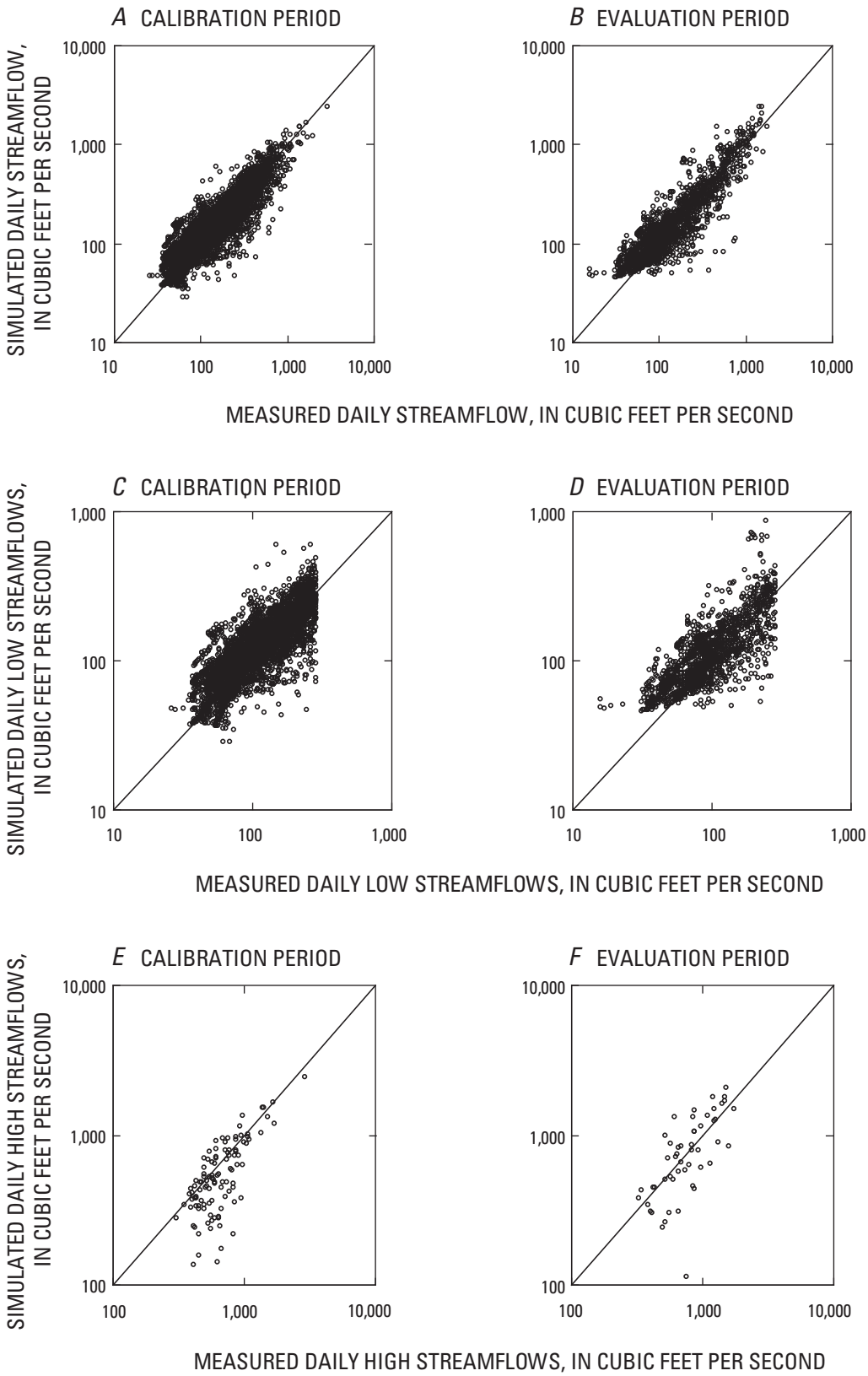


Figure 9. Calibrated and evaluation model output for *(A, B)* all daily streamflow, *(C, D)* low streamflows, and *(E, F)* high streamflows (calibration period simulates the period from October 1, 1985, through September 30, 1998; evaluation model output simulates the period from October 1, 2001, through September 30, 2006).

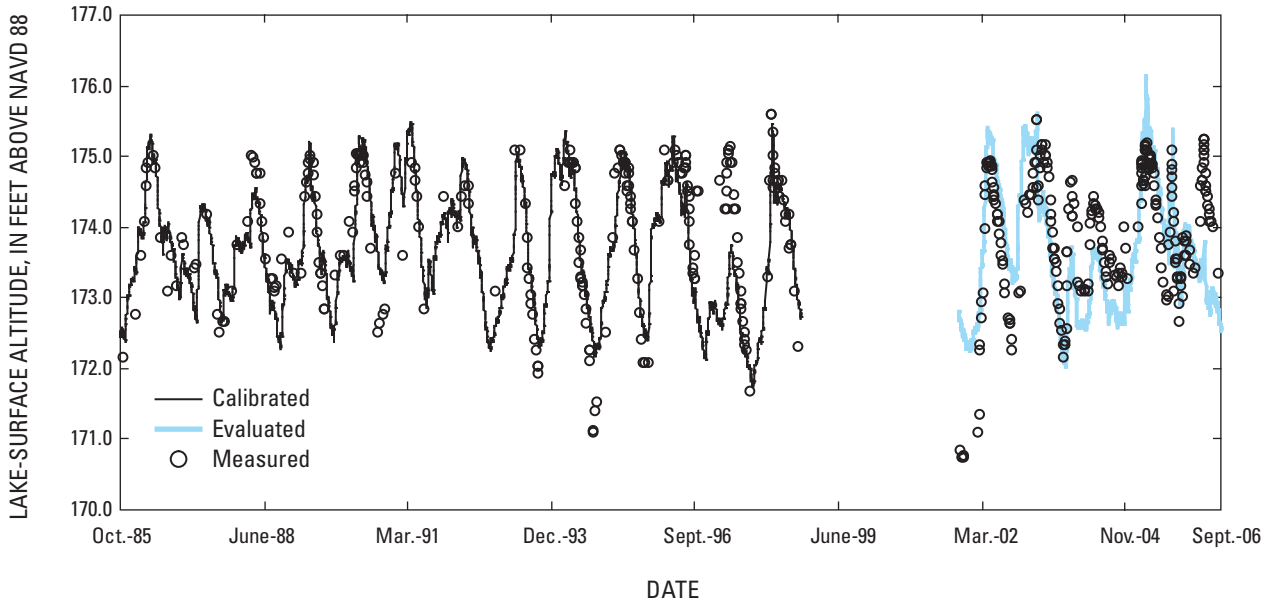


Figure 10. Calibrated and evaluation model output for Meddybemps Lake water-surface elevation (calibration period simulates the period from October 1, 1985, through September 30, 1998; evaluation model output simulates the period from October 1, 2001, through September 30, 2006).

Watershed Model Output for the Dennys River Basin

The calibrated water models of the Dennys River Basin provide simulated daily streamflow time series from October 1, 1985, through September 30, 2006, for many locations within the basin. This enables natural-resources managers to characterize the timing and quantity of water moving through the basin to support many endeavors, including geochemical calculations, water-use assessment, Atlantic salmon population dynamics and migration modeling, habitat modeling and assessment, and scenario testing (such as changes to Meddybemps Lake Dam rule curves, land-use changes, and changes in climate). The Dennys River Basin models make use of limited streamflow-gaging-station data and provide a method for characterizing subbasin hydrology—for example, three subbasins within the Dennys River main stem watershed model (Dead Stream, Curry Brook, and Venture Brook) had 2 years of intermittent streamflow data to use in the calibration process. Overall, comparison of the partial streamflow observations with model output was satisfactory. The resulting model output provides 21 years of daily streamflow time series for each subbasin for use by resource managers. Computation of mean monthly and annual streamflows for these subbasins compared favorably with streamflows estimated using statistical hydrologic models (regression equations) developed by Dudley (2004) (table 4). The close correspondence between PRMS and the statistical models lends an additional measure of confidence to the PRMS results for the Dennys River Basin.

Model output (for the period 1985–2006) provides daily streamflow time series at specific points of interest such as Meddybemps Lake (fig. 11). Time series of daily estimates of outflow from Meddybemps Lake can help evaluate dam operation in context with daily estimates of natural runoff contributions from tributary subbasins. For example, Dead Stream provides as little as 3 percent of the total basin outflow during the summer and as much as 8 percent during the spring; Curry and Venture Brooks each provide about 2 percent of the total basin outflow during the summer and about 4 to 5 percent during the spring; outflow from Meddybemps Lake contributes about one third of the total basin outflow during spring months when storage in Meddybemps Lake is increased, and contributes more than half (55 percent) of the total basin outflow during the summer (fig. 12).

Model output provides information regarding the apportioning of flow components of surface runoff, subsurface flow, and ground-water flow because the model explicitly simulates these physical processes (fig. 4). Total streamflow comprises these three components (fig. 13). This information can be used to support instream water-quality modeling if water-quality information (such as temperature and pH) is known or can be estimated for these components of streamflow. Additionally, this information can support water-budget and resource assessment investigations.

Table 4. Comparison of Precipitation Runoff Modeling System (PRMS) simulated mean monthly and mean annual streamflows (1985–2006) to statistically estimated mean monthly and mean annual streamflows computed using statewide regression equations (Dudley, 2004).

[All data in cubic feet per second; Model, streamflows computed on the basis of Dennys River Basin PRMS output; SREQ, streamflows computed using statewide regression equations]

	Dead Stream		Curry Brook		Venture Brook	
	Model	SREQ	Model	SREQ	Model	SREQ
January	13.0	12.3	7.45	7.87	6.42	7.24
February	14.7	12.4	6.26	8.01	4.92	7.43
March	32.9	27.7	15.6	18.6	11.1	17.4
April	26.7	34.7	18.6	19.9	17.6	17.0
May	12.8	15.2	8.08	7.98	8.19	6.51
June	5.92	9.22	3.70	5.21	3.65	4.44
July	3.19	3.77	2.00	2.06	2.00	1.74
August	2.94	2.78	1.82	1.53	1.87	1.30
September	2.30	3.26	1.62	1.82	1.77	1.55
October	6.91	7.01	4.38	4.05	4.34	3.48
November	17.4	14.4	9.83	8.52	8.74	7.37
December	18.8	16.8	10.4	10.4	9.09	9.39
Annual	13.1	13.2	7.48	7.63	6.64	6.56

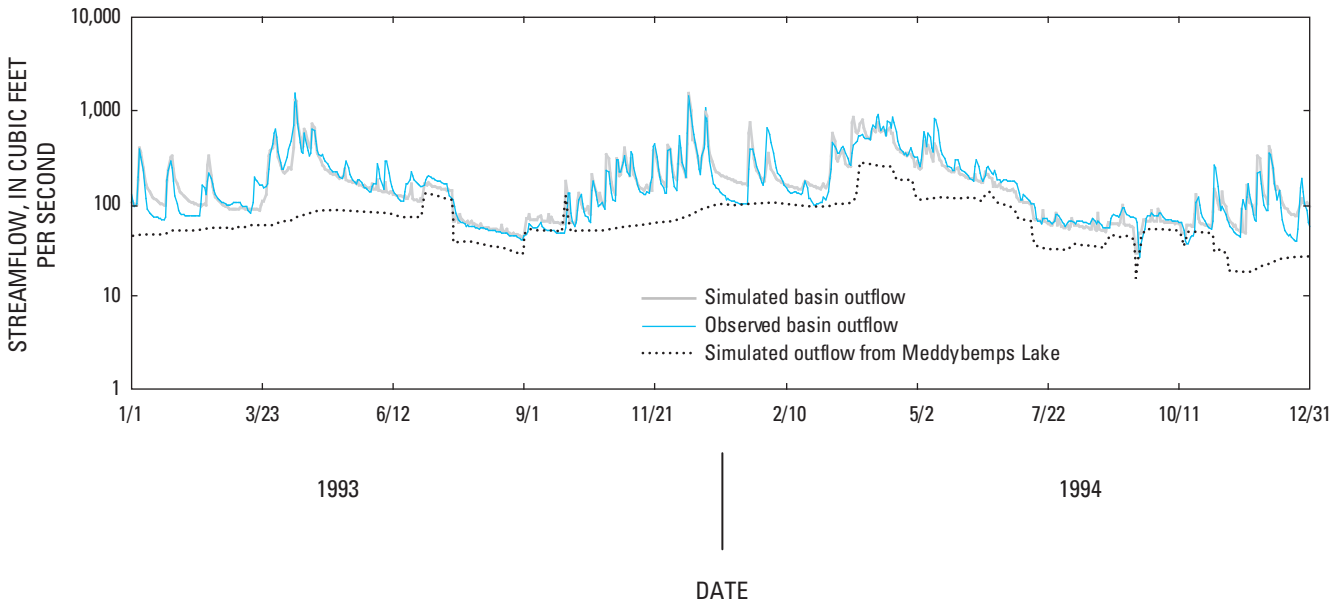


Figure 11. Time series showing simulated outflow from Meddybemps Lake on the basis of gate settings and simulated lake water-surface elevation as a function of modeled lake storage (total simulated outflow and measured outflow from streamflow-gaging station on the Dennys River at Dennysville (USGS station number 01021200) shown for comparison).

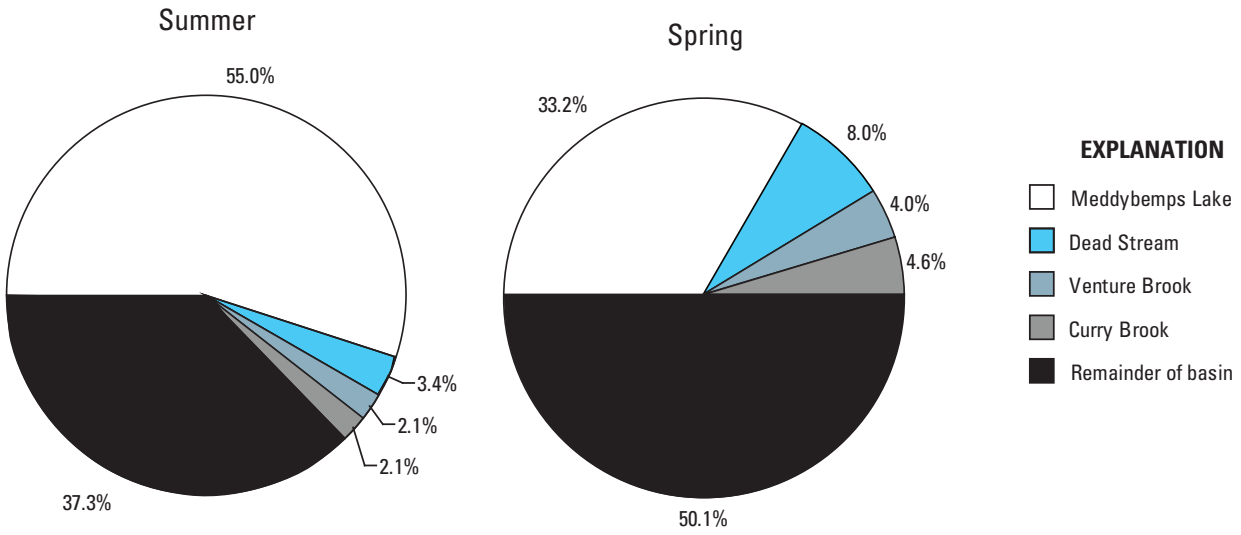


Figure 12. Apportioning of total simulated runoff from selected subbasins within the Dennys River Basin upstream from the streamflow-gaging station at Dennysville (01021200) during summer and spring (period of simulation from October 1, 1985, through September 30, 2006; summer—June, July, August; spring—March, April, May).

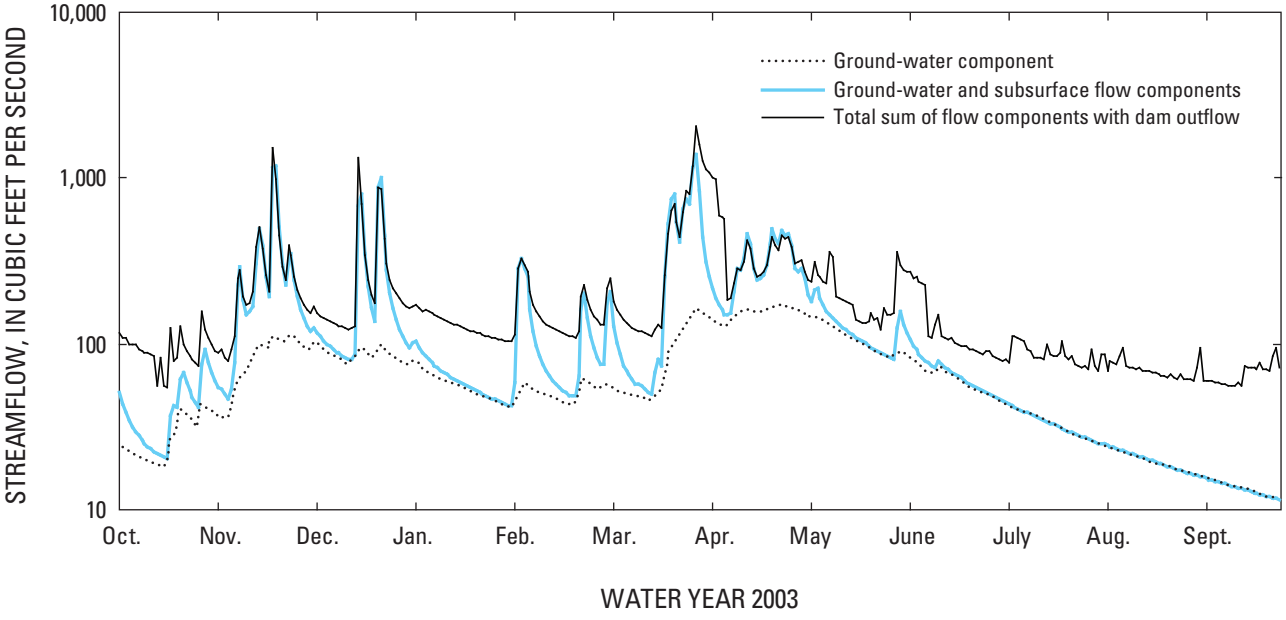


Figure 13. Simulated ground-water and subsurface flow partitioning of total streamflow.

With a calibrated model representative of current conditions, future traces of streamflow can be simulated using an ensemble streamflow prediction methodology (Day, 1985) to provide a probabilistic ensemble of possible future streamflow hydrographs. This methodology is currently used in applications for flood forecasting and reservoir management decision-making. PRMS recently has been integrated with a ground-water model in an application called GSFLOW (Markstrom and others, 2008) to support basin-scale ground-water/surface-water-resources investigations.

Watershed Model Uses, Uncertainties, and Limitations

The PRMS watershed models require precipitation and air temperature data as input to drive the computations; thus, the models are highly dependent on the accuracy of those data. In the case of this investigation, precipitation data were largely derived from a relatively sparse NWS meteorological data network, supplemented by data collected at USGS station number 445404067145201. Precipitation records used in this investigation provided a point coverage in and around the area of interest, and were interpolated to provide an areal distribution of precipitation within the modeled basin. Actual rainfall can vary greatly over small distances; thus, the available precipitation data set used in this investigation represents a large contributing factor as to why simulated streamflows do not exactly match measured streamflows on an event-by-event basis. Convective storms in the summer can produce relatively large amounts of rainfall outside of the basin; while it may be recorded at a NWS station nearby, no rain may have fallen in the basin itself, for example.

Temperature records were similarly derived from the relatively sparse NWS meteorological data network. Temperature data have a significant effect on simulated runoff; they are used in solar radiation computations and therefore computations of evapotranspiration. Air temperatures are a controlling factor in the determination of the form of precipitation (rain, snow, or mixture of both) and whether existing snowpack accumulates or melts—directly affecting the timing and amount released from frozen-water storage in the basins.

The computation of runoff by PRMS is a rudimentary accounting of flow at the subbasin scale, and not a rigorous simulation of the hydraulics of water movement; the location and velocity of channelized runoff within any subbasin is not explicitly modeled, nor are mechanisms such as gains from and losses to ground water through the streambed in any given reach. Whereas the new Lakes module simulates lake storage, regulated and unregulated outflows, and ground-water seepage, it does not explicitly model ice cover and snowpack accumulation and melt on lake surfaces.

Further uncertainties in the Dennys main stem model were associated with the regulation of outflow from Meddybemps Lake Dam. In particular, the outflow rating table, relating gate settings and lake levels to outflows, was provided to the USGS courtesy of the MBSRFH. Many outflow values for interpolated gate settings and lake levels were estimated for this investigation. Overflow at the outflow structures during very high lake-level conditions was estimated using broad-crested weir hydraulic approximations, introducing further uncertainties.

The lack of ground-water data in the basin introduces uncertainties in the models because there was little to no information available to guide the proper modeling of ground-water flow throughout the basin. All ground-water information had to be derived from existing streamflow records, which were heavily influenced by regulation at Meddybemps Lake Dam. Due to the importance of ground-water as part of total streamflow, information that quantifies ground-water contributions to streamflow (such as base-flow separation analyses) under natural conditions would improve the accuracy of existing and future watershed models in this area. Despite the lack of ground-water data and associated uncertainties, by calibrating simulated streamflow from these basin models to measured streamflow, the models provide a first-cut estimate at quantifying relative amounts of surface- and ground-water contributions to streamflow throughout the basin.

Overall, the basin models constructed in this investigation performed well, with the weakest simulations occurring during periods of extremely low flow and during the winter months (fig. 11). Presumably, better information regarding ground-water contributions to streamflow could help calibration of low-flow periods. Some periods of unsatisfactory model performance during winter months could be due to the lack of simulated ice cover for Meddybemps Lake, sensitivity of the model to air temperature data and the difficulty in properly modeling rain, snow, or mixed-phase precipitation events, and possible sensitivity to the changing permeability of soils during cold periods.

Characterizing streamflow contributions from subbasins in the basin and the relative amounts of surface- and ground-water contributions to streamflow throughout the basin will lead to a better understanding of water quantity and quality in the basin that will subsequently support the planning and execution of ongoing and future Atlantic salmon protection efforts. A calibrated watershed model can be used as tool to support a variety of cross-discipline and resource-management investigations and associated decision-making. Streamflow output from a watershed model can provide input to Atlantic salmon population dynamics and migration modeling, habitat modeling and assessment, for example. A broad variety of scenario testing can be done with watershed models to investigate potential changes to basin hydrology due to changes in water regulation (rule curves), water withdrawals, land-use changes (such as clear-cuts or urbanization), and changes in climate.

Summary

This study was done in cooperation with MBSRFH to characterize the quantity, variability, and timing of streamflow in the Dennys River. The study included a synoptic summary of historical streamflow data at a long-term streamflow gage, collecting data from an additional four short-term-streamflow gages, and the development and evaluation of a distributed-parameter watershed model for the Dennys River Basin. This study was undertaken because the Dennys River is an important habitat for wild Atlantic salmon, and helps advance the comprehensive recovery program developed in 1997 by the State of Maine. Modeling work in this study advances the development of water-management plans for each of the river basins home to protected Atlantic salmon.

The GIS Weasel was used to delineate the study basin and subbasins, and derive parameters for the geographic features of the basin using the U.S. General Soil Map, North American Land Cover Characteristics Data Base, U.S. Forest Type Groups, and U.S. Forest Density maps, and a digital elevation model (DEM) and its derivative surfaces. Parameters derived for each modeling response unit include: area, elevation, slope, aspect, vegetation type and density, precipitation interception capacities, and soil types.

The step-wise, multiple-objective calibration involved a four-step procedure in which model output was evaluated against four calibration data sets using computed objective functions for solar radiation, potential evapotranspiration, annual and seasonal water budgets, and daily streamflows. The calibration procedure involved thousands of model runs and was carried out using the software application Luca, which provides a user-friendly, systematic way to build and execute user-defined calibration procedures for any model constructed with USGS MMS. Luca uses the SCE global search algorithm to optimize model parameters.

The primary calibration effort went into the Dennys main stem watershed model. The Dennys main stem model was calibrated using 13 years of streamflow data collected from October 1, 1985, through September 30, 1998. Five years of streamflow record from October 1, 2001, through September 30, 2006, were used as an evaluation data set. Calibrated parameter values obtained for the Dennys main stem model were transferred to the Cathance Stream model, and a similar four-step SCE calibration procedure was performed; this effort demonstrated the applicability of the transfer of modeling information gained by modeling a nearby basin in the same region. Calibration was done for the Cathance Stream model using the 2 available years of record (May 20, 2004, through September 30, 2006). Due to the short period of record, a separate evaluation data set was not available for the Cathance Stream model.

The calibrated models of the Dennys River Basin provide simulated daily streamflow time series from October 1, 1985, through September 30, 2006, for nearly any location within the basin. This enables natural-resources managers to characterize the timing and quantity of water moving through the basin to support many endeavors, including geochemical calculations, water-use assessment, Atlantic salmon population dynamics and migration modeling, habitat modeling and assessment, and scenario testing (such as changes to Meddybemps Lake Dam rule curves, land-use changes, and changes in climate). Further, model output provides information regarding the apportioning of flow components of surface runoff, subsurface flow, and ground-water flow because the model explicitly simulates these processes. Total streamflow comprises these three components. This information can be used to support instream water-quality modeling if water-quality information (such as temperature and pH) is known or can be estimated for these components of streamflow.

The PRMS watershed models require precipitation and air temperature data as input to drive the computations; thus, the models are highly dependent on the accuracy of those data. In the case of this study, precipitation and temperature data were largely derived from a relatively sparse NWS meteorological data network.

The computation of runoff of flow by PRMS is a rudimentary accounting of flow at the subbasin scale, and not a rigorous simulation of the hydraulics of water movement; the location and velocity of channelized runoff within any subbasin is not explicitly modeled, nor are mechanisms such as gains from and losses to ground water through the streambed in any given reach. Whereas the new lakes module models lake storage, regulated and unregulated outflows, and ground-water seepage, it does not explicitly model ice cover and snowpack accumulation and melt on lake surfaces.

Further uncertainties in the Dennys main stem model were associated with the regulation of outflow from Meddybemps Lake Dam. The outflow rating table, relating gate settings and lake levels to outflows, was provided to the USGS courtesy of the MBSRFH. Many outflow values for interpolated gate settings and lake levels were estimated for this study. Overflow at the outflow structures during very high lake-level conditions were estimated using broad-crested weir hydraulic approximations, introducing further uncertainties.

The lack of ground-water data in the basin introduces uncertainties in the models because there was little to no information available to guide the proper modeling of ground-water flow throughout the basin. All ground water information had to be derived from existing streamflow records, which were heavily influenced by regulation from Meddybemps Lake. Due to the importance of ground water as part of total streamflow, information that quantifies ground-water contributions to streamflow (such as base-flow separation analyses) under natural conditions would improve the accuracy of existing and future watershed models in this area. Despite the lack of ground-water data and associated uncertainties, by calibrating simulated streamflow from these watershed models to measured streamflow, the models provide a first-cut estimate at quantifying relative amounts of surface- and ground-water contributions to streamflow throughout the watershed.

The watershed models constructed in this study performed well with the weakest simulations occurring during periods of extremely low flow and during the winter months. Better information regarding ground-water contributions to streamflow would help calibration of low-flow periods. Some unsatisfactory model performance during the winter months could be due to the lack of simulated ice cover for Meddybemps Lake, sensitivity of the model to air temperature data, the difficulty in properly modeling rain, snow, or mixed precipitation events, and possible sensitivity to the changing permeability of soils during cold periods.

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Appendix A—Documentation of the Modules Modified for Simulating Lakes in PRMS

There are four modules that were modified for the Dennys River model. These modules are documented herein.

NAME

`basin_sum_prms.f`

SPECIAL FEATURES

This is an enhancement of the standard PRMS module `basin_sum_prms.f.`

MODULE PROCESS (TYPE)

Summary

DEFINITION

Sums values for daily, monthly, yearly and total flow.

KEYWORDS

CREATION DATE

November 2006

PARAMETERS DECLARED

`basin_tsta_hru`–Index of MRU (HRU) to use for basin temperature.

`objfunc_q`– Index of the runoff station used as the observed runoff variable in the objective function calculation.

`print_freq`–Frequency for output data file: 0 = no output file; 1 = output run totals; 2 = output yearly totals; 4 = output monthly totals; 8 = output daily totals. For combinations, add index numbers, for example, daily plus yearly output = 10; yearly plus total = 3.

`print_objfunc`–Print objective functions (0 = no; 1 = yes).

`print_type`–Type of output data file: 0 = observed and predicted flow only; 1 = water balance table; 2 = detailed output.

`runoff_units`–Observed runoff units (0 = cubic feet per second (ft^3/s); 1 = cubic meters per second (m^3/s)).

VARIABLES DECLARED

`outlet_sta`–Index of observed-streamflow station that represents the basin outlet.

`basin_intcp_evap_mo`–Total monthly basin interception evaporation, in inches.

`basin_storage`–Storage in basin including ground-water, subsurface storage, soil moisture, snowpack, and interception, in inches.

`basin_et`–The sum of `basin_actet`, `basin_intcp_evap` and `basin_snowevap`.

`obsq_inches`–Observed streamflow, in inches.

`obsq_cms`–Observed streamflow for each streamflow station, in m^3/s.

`obsq_cfs`—Observed streamflow for each streamflow station, in ft^3/s.

`basin_ppt_mo`—Monthly total of `basin_ppt`, in inches.

`basin_net_ppt_mo`—Monthly total of `basin_net_ppt`, in inches.

`basin_max_temp_mo`—Maximum temperature for the month, F or C depending on units of data.

`basin_min_temp_mo`—Minimum temperature for the month, F or C depending on units of data.

`basin_potet_mo`—Monthly total of `basin_potet`, in inches.

`basin_actet_mo`—Monthly total of `basin_actet`, in inches.

`basin_et_mo`—Monthly total of `basin_et`, in inches.

`basin_snowmelt_mo`—Monthly total of `basin_snowmelt`, in inches.

`basin_gwflow_mo`—Monthly total of `basin_gwflow`, in inches.

`basin_ssflow_mo`—Monthly total of `basin_ssflow`, in inches.

`basin_sroff_mo`—Monthly total of `basin_sroff`, in inches.

`basin_stflow_mo`—Monthly total of `basin_stflow`, in inches.

`obsq_inches_mo`—Total monthly basin predicted streamflow, in ft^3/s.

`hru_et_cum`—Cumulative computed et for each hru for the year, in inches.

`basin_tsta`—Index of observed-temperature station used to compute basin temperature values.

EXTERNAL VARIABLES USED

`basin_area_inv`—Inverse of total basin area as sum of HRU areas, in $acres^{-1}$

`basin_soil_moist`—Basin area-weighted average for `soil_moist`, in inches.

`basin_gwstor`—Basin area-weighted average of ground-water storage, in inches.

`basin_ssstor`—Basin weighted average for subsurface reservoir storage, in inches.

`basin_intcp_stor`—Basin area-weighted average interception storage, in inches.

`basin_imperv_stor`—Basin area-weighted average for storage on impervious area, in inches.

`basin_pweqv`—Snowpack water equivalent on an HRU, in inches.

`basin_sfres_stor`—Basin reservoir storage, in inches.

`runoff`—Observed runoff for each stream gage, in ft^3/s.

`basin_ppt`—Area weighted adjusted average precipitation for basin, in inches.

`basin_actet`—Basin area-weighted average of `hru_actet`, in inches.

`basin_perv_et`—Basin area-weighted average of pervious area ET, in inches.

`basin_lakeevap`—Basin area-weighted average of lake evaporation, in inches.

`basin_intcp_evap`—Basin area-weighted evaporation from interception, in inches.

`basin_snowmelt`—Average snowmelt for total basin area, in inches.

`basin_soil_moist`—Basin area-weighted average for `soil_moist`, in inches.

`basin_intcp_stor`—Basin area-weighted average interception storage, in inches.

`basin_imperv_evap`—Basin area-weighted average for evaporation from impervious area, in inches.

`basin_imperv_stor`—Basin area-weighted average for storage on impervious area, in inches.

`basin_gwstor`—Basin area-weighted average of ground-water storage, in inches.

`basin_gwsink`—Basin area-weighted average of ground-water reservoir storage to the ground-water sink, in inches.

`active_hrus`—Number of active HRUs.

`hru_route_order`—Routing order of HRUs.

`basin_pweqv`—Basin area-weighted snowpack water equivalent, in inches.

`basin_ssstor`—Basin weighted average for subsurface reservoir storage, in inches.

`basin_sroff`—Basin surface runoff for timestep, in inches.

`basin_gwflow`—Basin ground-water flow for timestep, in inches.

`basin_ssflow`—Basin subsurface flow for timestep, in inches.

`orad`— Observed or computed solar radiation on a horizontal surface, in langleys.

`basin_net_ppt`—Basin area-weighted average `net_ppt`, in inches.

`basin_potet`—Basin area-weighted average of potential evapotranspiration, in inches.

`basin_snowevap`—Average evaporation and sublimation for total basin area, in inches.

`tmaxf`—HRU-adjusted daily maximum temperature, in degrees Fahrenheit.

`tminf`—HRU-adjusted daily minimum temperature, in degrees Fahrenheit.

`tmax`—Observed daily maximum temperature at each measurement station, in degrees Fahrenheit.

`tmax`—Observed daily minimum temperature at each measurement station, in degrees Fahrenheit.

`hru_actet`—Actual evapotranspiration on HRU, pervious and impervious, in inches.

`basin_stflow`—Sum of `basin_sroff`, `basin_ssflow` and `basin_gwflow` for timestep, in inches.

`basin_cfs`—Streamflow from basin, in ft^3/s.

`basin_2ndstflow`—Sum of basin streamflow from second outflow point, in inches.

DESCRIPTION

This summary is written for PRMS output at a daily time step. There are three types of summaries available. The first is a listing of the observed and predicted flow only. The second provides a table with values that will allow water balance computations and includes the basin-weighted averages for net precipitation, evapotranspiration from all sources, storage in all reservoirs, and the predicted and observed flows. The third is a detailed summary of the rainfall, outflow and state variables.

Any of the summaries may be requested in any combination of the available time increments, daily, monthly, yearly, or total for the model run.

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DEVELOPER NAME AND ADDRESS

George Leavesley
U.S. Geological Survey, WRD
Box 25046, MS 412, DFC
Denver, CO 80225
Telephone: 303-236-5026
Fax: 303-236-5034

NAME

`gwflow_casc_prms.f`

SPECIAL FEATURES

This is an enhancement of the standard PRMS module `gwflow_prms.f`

MODULE PROCESS (TYPE)

Ground-Water Flow

DEFINITION

Sums inflow to ground-water reservoirs and computes outflow to streamflow and to a sink if specified; includes cascading flow.

KEYWORDS

CREATION DATE

November 2006

PARAMETERS DECLARED

`ssr_gwres`—Index of the ground-water reservoir that will receive flow from each subsurface or gravity reservoir.

`hru_gwres`—Index of ground-water reservoir receiving excess soil water from each HRU.

`gwstor_init`—Storage in each ground-water reservoir at the beginning of a simulation, in inches.

`gwflow_coef`—Ground-water routing coefficient, which is multiplied by the storage in the ground-water reservoir to compute ground-water flow contribution to down-slope flow, in per day.

`gwsink_coef`—Ground-water sink coefficient, which is multiplied by the storage in the ground-water reservoir to compute the seepage from each reservoir to the ground-water sink, in per day.

`sfres_seep_elev`—Initial depth over which ground-water seepage occurs, in feet.

`elevsurf_init`—Initial lake surface elevation, in feet.

`hru_sfres`—Index of surface reservoir receiving excess water from HRU. If HRU does not feed a reservoir, then = 0.

VARIABLES DECLARED

`gw_upslope`—Ground-water flow received from upslope ground-water reservoirs, in acre-inches.

`gwres_stor`—Storage in each ground-water reservoir, in inches.

`gwres_flow`—Outflow from each ground-water reservoir, in inches.

`gwres_in`—Sum of inflows to each ground-water reservoir from all associated soil-zone reservoirs, in acre-inches.

`gwres_sink`—Amount of water transferred from ground-water reservoirs to the ground-water sink. This water is effectively routed out of the basin and will not be included in streamflow, in inches.

`gw_in_soil`—Sum of inflows to each ground-water reservoir from the soil-water excess of associated HRUs, in acre-inches.

`gw_in_ssr`—Sum of inflows to each ground-water reservoir from associated subsurface or gravity reservoirs, in acre-inches.

`res_to_gw`—Ground-water flow from reservoir to adjacent HRUs, in acre-inches.

`res_to_sink`—Ground-water flow from reservoir to adjacent HRUs, in acre-inches.

`basin_gwstor`—Basin area-weighted average of ground-water storage, in inches.

`basin_gwflow`—Basin area-weighted average of ground-water flow, in inches.

`basin_gwsink`—Basin area-weighted average of ground-water reservoir storage to the ground-water sink, in inches.

`basin_gwin`—Basin area-weighted average of inflow to ground-water reservoirs, in inches.

EXTERNAL VARIABLES USED

`basin_area_inv`—Inverse of total basin area as sum of HRU areas, in acres^{-1}.

`active_hrus`—Number of active HRUs.

`hru_route_order`—Routing order of HRUs.

`gwres_area`—Area of each ground-water reservoir computed by summing areas of HRUs that contribute to it, in acres.

`ssres_area`—Area of each subsurface reservoir computed by summing areas of HRUs that contribute to it, in acres.

`gwr_route_order`—Routing order of ground-water reservoirs.

`soil_to_gw`—Basin average excess soil water that flows directly to ground-water reservoirs, in inches.

`ssr_to_gw`—Seepage from subsurface reservoir storage to its associated ground-water reservoir each time step, in inches.

`sfres_vol`—Storage in each surface reservoir, in acre-feet.

`elevsurf`—Elevation of the lake surface, in feet.

`hru_perv`—Pervious area of each HRU, in acres.

`soil_to_gw`—Portion of excess soil water from an HRU that flows to its associated ground-water reservoir, in inches.

`ncascade_gwr`—Number of cascade links for ground-water reservoir cascade routing.

`hru_type`—Type of each HRU (0 = inactive; 1 = land; 2 = lake; 3 = swale).

`active_gwrs`—Number of active ground-water reservoirs.

`strm_seg_in`—Flow in stream segments as a result of cascading flow.

DESCRIPTION

This module is a modification of the PRMS `gwflow_prms.f` module to include the simulation of surface reservoirs (lakes). Module modifications compute changes in storage (as a function of lake area and water-surface elevation) on the basis of the difference between lake inflows and outflows. Inflows are routed from upstream MRUs. Lake outflows are modeled either by a broad-crested weir hydraulic approximation (natural outflow) or a user-defined outflow rating as a function of gate opening and lake water-surface elevation. Ground-water seepage is modeled using a seepage coefficient and depth over which seepage occurs. For more details, refer to the `gwflow_prms.f` module documentation.

DEVELOPER NAME AND ADDRESS

George Leavesley
U.S. Geological Survey, WRD
Box 25046, MS 412, DFC
Denver, CO 80225
Telephone: 303-236-5026
Fax: 303-236-5034

NAME

`obs_lake_prms.f`

SPECIAL FEATURES

This is a new module.

MODULE PROCESS (TYPE)

Read input variables.

DEFINITION

Reads input variables from the designated data file.

KEYWORDS

CREATION DATE

November 2006

PARAMETERS DECLARED

VARIABLES DECLARED

`sfr_elev`—Elevation of the lake surface, in feet.

`gate_ht`—Height of the gate opening at the dam, in inches.

EXTERNAL VARIABLES USED

None.

DESCRIPTION

This module reads the MMS input data file for the PRMS model. The MMS data file has an ASCII flat-file format and is created by the user. The input variables have a defined order of input. The format is a short multi-line header, a separator line, and then the data. The first line of the header contains a description of the data file. This description has a limit of 80 characters. The remainder of the header describes the data fields in each row. Each line contains the variable name and the number of values for that variable in each row. The number of values must be less than or equal to the current dimension of that variable. The order of the variables is fixed and reflects the order of occurrence in each row.

A separator line indicates the end of the header information and the beginning of the data. This line must consist of at least four pound symbols (####).

The data lines start after the separator line. Fields in the data line are separated by white space. The first six fields of the data line are reserved for the time stamp. The fields are year, month, day, hour, minute, and second respectively (yyyy-mm-dd hh:mm:ss). The remaining columns must correspond to the order and number of values specified in the header section of the file. An error is reported if the data requested by the modules do not match the header. Extra values on the line will be ignored. The variable `route_on` must be included when storm-mode computations are desired.

REFERENCES

Leavesley, G.H., Lichty, R.W., Troutman, B.M., and Saindon, L.G., 1983, Precipitation-runoff modeling system–User's manual: U.S. Geological Survey Water-Resources Investigations Report 83–4238, 207 p.

DEVELOPER NAME AND ADDRESS

George Leavesley
U.S. Geological Survey, WRD
Box 25046, MS 412, DFC
Denver, CO 80225
Telephone: 303-236-5026
Fax: 303-236-5034

NAME

`strmflow_lake_prms.f`

SPECIAL FEATURES

This is a new module.

MODULE PROCESS (TYPE)

Calculates daily streamflow and flow from lakes and within stream segments.

DEFINITION

Procedure to compute daily streamflow as the sum of surface, subsurface, and ground-water flow contributions at the basin outlet.

KEYWORDS

CREATION DATE

November 2006

PARAMETERS DECLARED

`sfres_type`—Type of surface reservoir (8 = Puls routing; 9 = Linear routing; 10 = Flow through; 11 = Broad-crested weir; 12 = Rating table).

`hru_sfres`—Index of surface reservoir receiving excess water from HRU. If HRU does not feed a reservoir, then = 0.

`sfres_hru`—Index of HRU that is the surface reservoir.

`sfres_gw`—Index of ground-water reservoir assigned to surface reservoir.

`sfres_init`—Initial storage in each surface reservoir, in ft^3/s-days.

`sfres_qro`—Initial daily mean outflow from each storage reservoir, in ft^3/s.

`sfres_din1`—Surface reservoir inflow from the previous time step, in ft^3/s.

`sfres_coef`—Coefficient to route reservoir storage to streamflow using the equation: `res_flow` = `sfres_coef` * `res_stor`, in inverse days.

`o2`—Outflow values in outflow/storage table for Puls routing, in ft^3/s.

`s2`—Storage values in outflow/storage table for Puls routing, in ft^3/s-days.

`nsos`—Number of storage/outflow values in table for Puls routing.

`weir_coef`—Broad-crested weir coefficient.

`weir_len`—Broad-crested weir length, in feet.

`elev_outflow`—Elevation of the outflow point, in feet.

`seg_res_id`—Reservoir ID number for a reservoir stream segment. 0 = open channel segment, 1-n = reservoir ID.

`rate_table`—Rating table with stage (rows) and gate opening (columns), in ft^3/s.

`tbl_stage`—Stage values for each row in the rating table, in feet.

`tbl_gate`—Gate openings for each column in the rating table, in inches.

`elevsurf_init`—Initial lake surface elevation, in feet.

`sfres_vol_init`—Initial lake volume, in acre-feet.

`sfres_out2`—Switch to specify a second outflow point from reservoir.

`sfres_out2_a`—Outflow computation coefficient in equation Q = (`sfres_out2_a * elevsurf`) - `sfres_out2_b`, in $ft^3/s/ft$.

`sfres_out2_b`— Outflow computation coefficient in equation Q = (`sfres_out2_a * elevsurf`) - `sfres_out2_b`, in $ft^3/s/ft$.

`basin_cfs_init`—Initial basin streamflow, required if the first timestep is a storm period, in ft^3/s.

`hru_area`—Area of each HRU, in acres.

`seg_type`—Type of stream segment; 1 = Open channel, 2 = Reservoir or Lake.

`strmseg_down_id`—Index number of the downstream segment to which this stream segment flows.

VARIABLES DECLARED

`basin_stflow`—Sum of `basin_sroff`, `basin_ssflow` and `basin_gwflow` for timestep, in inches.

`basin_2ndstflow`—Sum of basin streamflow from second outflow point, in inches.

`basin_cfs`—Streamflow from basin, in ft^3/s.

`basin_cms`—Streamflow from basin, in m^3/s.

`q_segment`—Outflow from stream segment, in ft^3/s.

`basin_sroff_cfs`—Basin surface runoff for timestep, in ft^3/s.

`basin_ssflow_cfs`—Basin subsurface flow for timestep, in ft^3/s.

`basin_gwflow_cfs`—Basin ground-water flow for timestep, in ft^3/s.

`sfres_sto`—Storage in each surface reservoir, in ft^3/s-days.

`sfres_vol`—Storage in each surface reservoir, in acre-feet.

`sfres_outq`—Outflow from each surface reservoir, in ft^3/s.

`sfres_outq2`—Outflow from second point in each surface reservoir, in ft^3/s.

`sfres_outcms`—Outflow from each surface reservoir, in m^3/s.

`sfres_area`—Sum of HRU areas contributing to this surface reservoir, in acres.

`din1`—Storage reservoir inflow from the previous time step, in ft^3/s.

`elevsurf`—Elevation of the lake surface, in feet.

`sfres_invol`—Volume of lake inflow, in acre-inches.

`sfres_outvol`—Volume of lake outflow, in acre-inches.

`basin_sfres_stor`—Basin reservoir storage, in inches.

EXTERNAL VARIABLES USED

`basin_area_inv`—Inverse of total basin area as sum of HRU areas, in acres^{-1}.

`active_hrus`—Number of active HRUs.

`hru_route_order`—Routing order of HRUs.

`strm_seg_in`—Flow in stream segments as a result of cascading flow, in ft^3/s.

`upslope_hortonian`—Surface runoff received from HRUs up slope, in inches.

`basin_sroff`—Basin area-weighted average of surface runoff, in inches.

`basin_gwflow`—Basin area-weighted average of ground-water flow, in inches.

`basin_ssflow`—Basin weighted average for subsurface reservoir outflow, in inches.

`gate_ht`—Height of the gate opening at the dam, in inches.

`upslope_interflow`—Interflow received from HRUs up slope, in inches.

`upslope_dunnianflow`—Dunnian runoff received from HRUs up slope, in inches.

`gw_upslope`—Ground-water flow received from upslope ground-water reservoirs, in acre-feet.

`hru_actet`—Actual evapotranspiration on HRU, pervious and impervious, in inches.

`hru_ppt`—Adjusted precipitation on each HRU, in inches.

`pkwater_equiv`—Snowpack water equivalent on an HRU, in inches.

`snowmelt`—Snowmelt from snowpack on an HRU, in inches.

`res_to_gw`—Ground-water flow from reservoir to adjacent HRUs, in acre-inches.

`res_to_sink`—Ground-water flow from reservoir to adjacent HRUs, in acre-inches.

DESCRIPTION

This module is a variation of the PRMS `strmflow_st_prms.f` module to include the simulation of surface reservoirs (lakes). For more details, refer to the `strmflow_st_prms.f` and `gwflow_casc_prms.f` modules documentation.

DEVELOPER NAME AND ADDRESS

George Leavesley
U.S. Geological Survey, WRD
Box 25046, MS 412, DFC
Denver, CO 80225
Telephone: 303-236-5026
Fax: 303-236-5034

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