Chapter 7

MMS - PRMS

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I. INTRODUCTION

The Precipitation-Runoff Modeling System (PRMS) (Leavesley et al., 1983; Leavesley and Stannard, 1995) is a modular-design, distributed-parameter, physical-process watershed model that was developed to evaluate the effects of various combinations of precipitation, climate, and land use on watershed response. Response to normal and extreme rainfall and snowmelt can be simulated to evaluate changes in water-balance relations, flow regimes, flood peaks and volumes, soil-water relations, sediment yields, and ground-water recharge.

PRMS was originally developed as a single FORTRAN program composed of subroutines, each representing an individual process in the hydrologic cycle. For the processes related to temperature distribution, solar-radiation distribution, evapotranspiration, and surface runoff, two or more computational methods were included in the subroutines. A specific method was selected at run time using the model parameter file. This concept enabled the creation and application of a model that was most appropriate for a given application. A long-term goal was to expand the available process simulation capabilities of PRMS over time.

While reasonable in concept and computationally efficient, experience with adding process components to the original code proved the modular-design and user-modifiable features of that version to be less than adequate. As a result, the architecture and modular structure of PRMS were redesigned. The new design formed the basis for the USGS Modular Modeling System (MMS) (Leavesley et al., 1996), in which PRMS now resides. The basic hydrologic process formulations in PRMS described by Leavesley and Stannard (1995) were maintained in the MMS version. However, the use of MMS has enabled the addition of new process algorithms and the enhancement of many of the features and capabilities of PRMS.

The purpose of this paper is to provide an overview of MMS-PRMS, its modular components, model support and analysis capabilities, and selected applications. More detailed discussions regarding individual components can be found in the module documentation and cited references for each component.

II. MODULAR MODELING SYSEM (MMS)

A basic premise in the development of MMS, as with PRMS, is that there are no universal models. The optimal model for a given application is one in which the process conceptualizations in the model are most appropriate for the problem objectives, data constraints, and spatial and temporal scales of the application.

A central component of MMS is a master library that contains compatible modules for simulating a variety of water, energy, and biogeochemical processes. A model for a specified application is created by coupling appropriate modules from the library. If existing modules cannot provide appropriate process algorithms, new modules can be developed and incorporated into the library. This modular approach to model design and construction provides the ability to develop, select, integrate, and apply a set of process modules that best meet the optimal model selection criteria.

MMS was developed to (1) support development, testing, and evaluation of physical-process modules; (2) facilitate integration of user-selected modules into operational physical-process models; (3) facilitate the coupling of models for application to complex, multidisciplinary problems; and (4) provide a wide range of analysis and support tools for research and operational applications. MMS is a modular modeling framework that uses an Open Source software approach to enable all users to collaboratively address the many complex issues associated with the design, development, and application of hydrologic and ecosystem models. While MMS was created based on the conceptual design of PRMS , MMS is much more than simply an extension of PRMS. Other models integrated into MMS include TOPMODEL(Beven et al., 1995), the Sacramento Model (), SNOW-17 (), and the Snowmelt Runoff Model (SRM) ().

MMS supports the integration of models and tools at a variety of levels of modular design. Design levels include individual process models, tightly coupled models, loosely coupled models, and fully integrated decision support systems. A variety of geographic information system (GIS), optimization and sensitivity-analysis, forecasting, visualization, and statistical tools are provided to support model development, application, and analysis. The integration and application of these tools with PRMS are discussed in more detail in the following sections of this chapter.

III. PRMS

A. Space and Time Concepts

Distributed-parameter capabilities are provided by partitioning a watershed into units, using characteristics such as slope, aspect, elevation, vegetation type, soil type, and precipitation distribution. Each unit is assumed to be homogeneous with respect to its hydrologic response and to the characteristics listed above; each unit is called a hydrologic response unit (HRU). A water balance and an energy balance are computed daily for each HRU. The sum of the responses of all HRUs, weighted on a unit-area basis, produces the daily watershed response.

Watershed response can be simulated at both a daily and a storm time scale. In the daily mode, hydrologic components are simulated as daily average or total values. Streamflow is computed as a mean daily flow. In the storm mode, selected hydrologic components are simulated at time intervals that can range from less than one to 60 minutes. The time step must be constant within a storm but could be different for each storm. Continuity of mass is maintained as the model moves from daily mode to storm mode and back to daily mode. Storm hydrographs and sediment yields for selected rainstorms can be simulated in storm mode. Sediment-modeling capabilities are provided only in the storm mode.

For storm-mode computations, a watershed is conceptualized as a series of interconnected flow-plane and channel segments. An HRU is considered the equivalent of a single flow plane. The shape of the flow plane is assumed to be rectangular, with the length of one side of rectangle equal to the length of the channel segment that receives runoff from the flow plane. The flow-plane width is computed by dividing the HRU area by the channel segment length. All flow planes are assumed to connect to a channel segment. Cascading flow planes are not currently supported, but a module to support this capability is being developed.

B. PRMS Process Modules

The process components simulated in PRMS are shown schematically in Figure 1. The processes shown are generic in name. Thus Figure 1 is a template for model design and not a flow chart describing a unique set of process algorithms. In the MMS design, process selection is now a component part of the model building process. Each alternative computational method for a given process is a module that can be combined with other process and accounting modules to build a unique model for a specific application.

Model building in MMS is accomplished using an interactive model builder graphical user interface (GUI) termed Xmbuild. Xmbuild enables the user to select and link modules to create a model. Modules are designed so that the output from one module is the input to other process modules. Xmbuild enables users to view inputs and outputs for each module and to search the module library for all modules that provide the necessary inputs for a selected module. Using this search and select procedure, a user-defined model can be constructed. Module inputs and outputs include a units attribute that can be checked to insure module compatibility. Plans include the development of an expert system to assist users in module selection based on future research to identify the most appropriate modules for various combinations of problem objectives, data constraints, and spatial and temporal scales of application.

A detailed description of the computational methods and equations used in PRMS was provided in Leavesley et al. (1983) and Leavesley and Stannard (1995). This material has been rewritten and is included in detailed documentation for each PRMS module. This documentation is provided with the distribution of MMS-PRMS and is also available on the MMS web site. Module documentation includes the listing and definition of all parameters and variables used in the module, the equations used in the computational algorithms, and a text description of the module process and function.

A major difference between the old and new documentation is that parameter and variable names have been changed in the new version to make them more descriptive of their function and use. The length of parameter and variable names in the original version of PRMS was limited by the available version of FORTRAN 77 to six characters. In the new module distribution, current versions of FORTRAN 77 enable the use of much longer names.

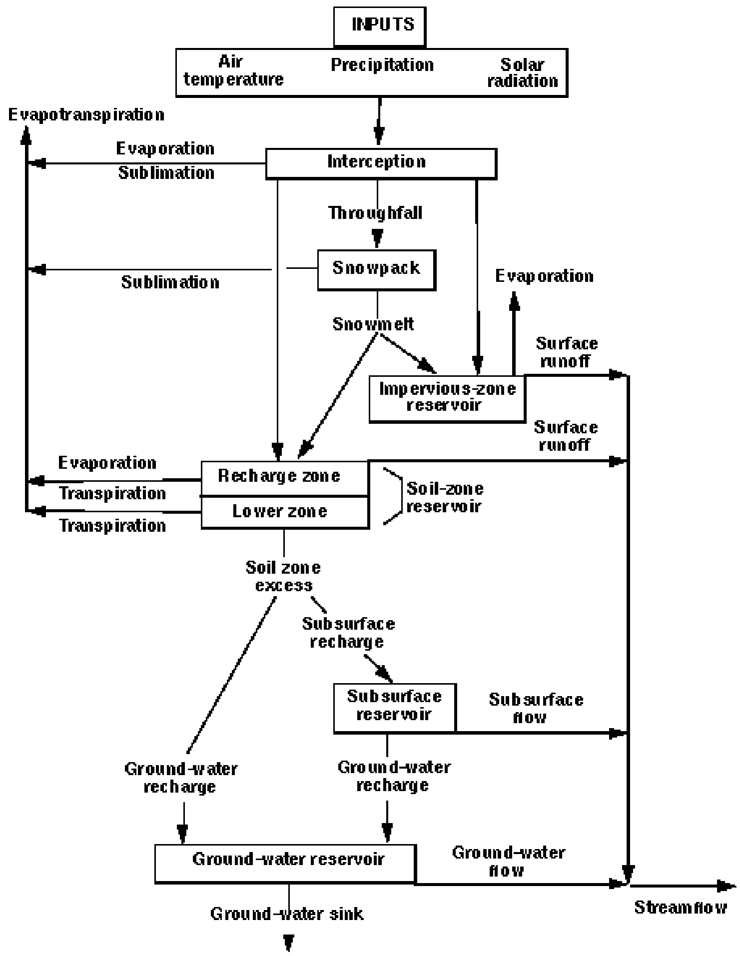

Figure 1. Schematic diagram of the conceptual watershed system and its inputs. (Modified from Leavesley, et al., 1983)

Translation tables to go from names in the original code to the names in the new code and vice versa are available on the MMS web site. New PRMS users should start with the MMS-PRMS module documentation to avoid confusion.

A summary description of PRMS process components is provided below. For a detailed description of individual process modules and the equations used, the reader is referred to the PRMS module documentation. The modules associated with each process component are highlighted in brackets [].The modules for PRMS daily mode are listed in Table 1.

Table 1. PRMS Daily mode modules.

Process	Module	Description
Basin definition		
	basin_prms.f	Basin and hru features
Observed data		
	obs_prms.f	Read observed data
Temperature distribution		
	temp_1st_prms.f	Use one climate station and a monthly lapse rate for each HRU
	temp_2st_prms.f	Use two climate stations to compute daily lapse rate for each HRU
	xyz_dist.f	Uses latitude, longitude, and elevation of climate stations and HRUs
Precipitation distribution		
	precip_prms.f	Use one climate station and a user-defined correction factor for each HRU
	precip_laps_prms.f	Use two climate stations to compute correction factor for each HRU
	xyz_dist.f	Uses latitude, longitude, and elevation of climate stations and HRUs
Solar radiation computation		
	soltab_prms.f	Compute potential solar radiation on horizontal surface and each HRU slope-aspect combination
Solar radiation distribution		
	ccsolrad_prms.f	Estimate actual solar radiation on each HRU using daily air temperature range (max-min)
	ddsolrad_prms.f	Estimate actual solar radiation on each HRU using daily maximum air temperature
	ddsolrad_xyz_prms.f	ddsolrad version for use with xyz_dist.f
Potential evapo-transpiration		
	potet_hamon_prms.f	Compute Hamon PET
	potet_jh_prms.f	Compute Jensen-Haise PET
	potet_epan_prms.f	Compute pan evaporation PET
	potet_ep_not_prms.f	Compute pan evaporation PET and no temperature data available
Interception		
	intcp_prms.f	Compute net precipitation and interception storage and loss
Snow		
	snowcomp_prms.f	Compute snowpack accumulation and melt
Surface runoff		
	srunoff_carea_prms.f	Compute surface runoff using linear contributing area method
	srunoff_smidx_prms.f	Compute surface runoff using non-linear contributing area method

Table 1 continued. PRMS daily mode modules.

Process	Module	Description
Soil zone		
	smbal_prms.f	Soil zone accounting and AET computation
Subsurface		
	Ssflow_prms.f	Subsurface reservoir and flow
Ground water		
	Gwflow_prms.f	Ground water reservoir and flow
Streamflow (flow and reservoirs)		
	Strmflow_prms.f	
Summary		
	Basin_sum_prms.f	Basin summary computations
	Hru_sum_prms.f	HRU summary computations

1. PRMS Daily-Mode

Climate Components. Daily-mode model inputs are daily precipitation, maximum and minimum air temperature, and solar radiation [*obs_prms.f*]. The energy inputs of air temperature and solar radiation are used in the computation of evaporation, transpiration, sublimation, and snowmelt. These point data are extrapolated to each HRU using a set of adjustment coefficients developed from regional climate data. The coefficients typically include the effects of HRU elevation, slope, aspect, and distance to one or more measurement sites. Measured maximum and minimum daily air-temperature data are adjusted using monthly [*temp_1st_prms.f*] or daily [*temp_2st_prms.f*] lapse rates and the elevation difference between a climate station and each HRU.

Precipitation amount on each HRU is computed by multiplying point measurements by a monthly correction factor. The correction factor attempts to account for a number of sources of measurement variability and error including the effects of elevation, spatial variation, topography, gage location, deficiencies in gage catch due to the effects of wind, and other factors. One distribution method enables the user to identify the precipitation gauge most representative of an HRU and to specify the monthly correction factor to be used to compute HRU precipitation amount [*precip_prms.f*]. A second method is similar in that the gauge most representative of an HRU is selected. However, a second gauge is also selected for use in computing the monthly correction factor as a function of the ratio of the mean monthly precipitation at each station and their difference in elevation [*precip_plaps_prms.f*].

A third method uses a multiple linear regression (MLR) approach to distribute daily measured precipitation data from a group of stations to each HRU based on the longitude (x), latitude (y), and elevation (z) of the measurement stations and the HRUs (Hay et al., 2000; Hay and Clark, 2000) [*xyz_dist.f*]. To account for seasonal climate variations, the MLR equation is developed for each month using a set of independent variables of x, y, and z (xyz) from a user-selected set of climate stations within and outside a basin.

The monthly MLR equations describe the spatial relations between monthly precipitation and the independent xyz variables. To estimate the daily value of precipitation for each HRU, a mean daily value of precipitation for all, or a user-defined subset, of the climate stations, and the corresponding mean x, y, and z for this set of stations, is used with the "slope" of the monthly MLR equation to estimate a unique y-intercept (b_0) for that day. Using this b_0 value and the x, y, and z values for each HRU, the MLR equation is then used to compute precipitation on each HRU. A monthly adjustment factor for rainfall and for snow can can also be user-specified to modify the mean daily value to account for the sources of measuement error list above.

When the xyz procedure is selected for precipitation distribution,it is also used to compute maximum and minimum air temperature on each HRU. The climate station set selected for temperature computation, however, may be different than the climate station set selected for precipitation distribution.

Precipitation form (rain, snow, or mixture of both) on each HRU is estimated from the HRU maximum and minimum daily air temperatures and their relation to a base temperature (Willen et al., 1971). The base temperature is the temperature at or below which snow is assumed to occur.

Measured shortwave radiation, on a horizontal surface, is adjusted to estimate daily shortwave radiation received on the slope-aspect combination of each HRU using a method described by Swift (1976). Missing shortwave radiation data are estimated using one of two methods. The first is a modification of the degree-day method described by Leaf and Brink (1973) [*ddsolrad_prms.f*]. This method was developed for a section of the Rocky Mountain region of the United States. It is most applicable to this region where predominantly clear skies prevail on days without precipitation. The second procedure uses a relation between sky cover and daily range in air temperature demonstrated by Tangborn (1979) and a relation between solar radiation and sky cover developed by Thompson (1976) [*ccsolrad_prms.f*]. This procedure is applicable to more humid regions where extensive periods of cloud cover occur with and without precipitation.

Land-phase Components. Interception is computed as a function of vegetation cover density and the storage available on the predominant vegetation type of an HRU [*intcp_prms.f*]. Vegetation types are defined as bare, grass, shrubs, and trees. Variations in cover density by season, and variations in interception storage by vegetation type and season are considered. Precipitation amount is decreased by interception and becomes net precipitation delivered to the watershed surface. Intercepted rain is assumed to evaporate at a free-water-surface rate. Intercepted snow is assumed to sublimate at a rate that is expressed as a user-defined percentage of potential evapotranspiration.

Net precipitation reaches the snowpack or soil surface where it accumulates in the snowpack or is available for surface runoff and infiltration. Daily surface runoff from rainfall on pervious, snow-free HRU's is computed using a contributing-area concept (Dickinson and Whiteley, 1970; Hewlett and Nutter, 1970). Net precipitation not becoming surface runoff infiltrates the soil surface. The percent of an HRU contributing to surface runoff can be computed as either a linear [*srunoff_carea_prms.f*] or a nonlinear [*srunoff_smidx_prms.f*] function of antecedent soil moisture and rainfall amount.

Surface runoff from snowmelt is computed only on a daily basis. Snowmelt runoff from pervious areas is assumed to occur only when the soil zone of an

HRU reaches field capacity. At field capacity, a user-defined, daily maximum infiltration rate is assumed. Any daily snowmelt in excess of this maximum infiltration rate is assumed to become surface runoff. For impervious areas, snowmelt first satisfies available retention storage, and the remaining snowmelt becomes surface runoff.

The soil and subsurface components of a watershed system are conceptualized as a series of reservoirs, the responses of which combine to produce the total watershed response. 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. The maximum available water-holding capacity of the soil-zone reservoir is the difference between field capacity and wilting point of the profile.

The soil-zone reservoir is treated as a two-layered system. The upper zone is termed the recharge zone and the remaining profile is the lower zone. Evaporative losses from the recharge zone occur from evaporation and transpiration; losses from the lower zone are assumed to occur only through transpiration. Water storage in the soil-zone reservoir is increased by infiltration of rainfall and snowmelt and is decreased by evapotranspiration [*smbal_prms.f*].

A choice of three procedures are available to compute potential evapotranspiration (PET). One procedure uses daily pan-evaporation data and a monthly pan-adjustment coefficient [*potet_epan_prms.f*; *potet_ep_not_prms.f*]. A second procedure uses the Hamon method to compute PET as a function of daily mean air temperature and possible hours of sunshine (Hamon, 1961) [*potet_hamon_prms.f*]. The third procedure is a modified Jensen-Haise technique (Jensen et al., 1969) that computes PET using air temperature, solar radiation, and two coefficients that can be estimated using regional air-temperature, elevation, vapor-pressure, and vegetation data [*potet_jh_prms.f*].

Actual evapotranspiration (AET) is computed as a function of soil type, water currently available in the soil-zone reservoir, and the storage capacity of the soil-zone reservoir using an approach developed by Zahner (1967) [*smbal_prms.f*]. When available water is nonlimiting, AET equals PET. PET is first satisfied from interception storage, retention storage on impervious surfaces, and evaporation/sublimation from snow surfaces. Remaining PET demand is then applied to the soil-zone storage. AET is computed separately for the recharge zone and the lower zone using the unsatisfied PET demand and the ratio of currently available water in the soil zone to its maximum available water-holding capacity. AET computed for the recharge zone is used first to satisfy PET; any remaining demand is attempted to be met from the lower zone. Relations between AET and available soil moisture are defined for three soil types; sand, loam, and clay.

The active transpiration period is user-defined by a beginning and ending month. The specific date of the start of transpiration is computed for each HRU using a threshold accumulated degree-day approach. The sum of the maximum daily air temperatures is accumulated for each HRU, starting on the first day of the month transpiration is assumed to begin. When this sum exceeds a user-defined threshold value, transpiration is assumed to begin. Transpiration is assumed to end on the first day of the month specified as the month transpiration ends.

Infiltration to the HRU soil zone must fill the recharge zone before water will move to the lower zone. When the soil-zone reservoir reaches maximum storage capacity, additional infiltration is routed to the subsurface and ground-water reservoirs. The apportioning of soil water in excess of the maximum storage capacity to the subsurface and ground-water reservoirs is done using a user-defined daily ground-water recharge rate [*smbal_prms.f*]. Daily ground-water reservoir inflow may be equal to or less than the recharge rate, depending on the magnitude of soil-water excess. When soil-water excess is larger than the recharge rate, the difference becomes subsurface reservoir inflow.

The subsurface reservoir simulates the relatively rapid component of flow that may occur in the saturated-unsaturated and ground-water zones during periods of rainfall and snowmelt [*ssflow_prms.f*]. The subsurface reservoir can be defined as being linear or nonlinear.

The ground-water reservoir simulates the slower component of flow from the ground-water zone [*gwflow_prms.f*]. It is conceptualized as a linear reservoir and is assumed to be the source of all baseflow. Inflow to the ground-water reservoir can be from both soil-water excess [*smbal_prms.f*] and one or more subsurface reservoirs. The vertical movement of water from a subsurface reservoir to a ground-water reservoir is computed as a function of the current volume of storage in subsurface reservoir and a linear routing coefficient [*ssflow_prms.f*]. The movement of water through the ground-water reservoir to points outside the surface drainage boundary is treated using a ground-water sink which is computed as a function of storage in the ground-water reservoir and a linear routing coefficient.

The shape of the baseflow recession of the simulated hydrograph will be affected by the relative proportion of ground-water recharge from the two source terms. Recharge from the soil zone occurs only on days when the maximum storage capacity of the soil zone reservoir is exceeded while recharge from the subsurface reservoir occurs every day that water is available in the subsurface reservoir.

Snow Components. The snow components simulate the initiation, accumulation, and depletion of a snowpack on each HRU [*snowcomp_prms.f*]. A snowpack is maintained and modified on both a water-equivalent basis and as a dynamic-heat reservoir. A snowpack water balance is computed daily and an energy balance is computed twice each day for 12-hour periods (designated day and night). The energy-balance computations are a combination of equations and functional relationships taken or derived from several sources. The conceptual model for the snowpack system and its energy relations is one described by Obled and Rosse (1977). The conceptual snowpack system and the components of the snowpack energy balance are shown in Figure 2.

Shortwave net radiation for the snow surface is computed as a function of slope and aspect of the HRU, the albedo of the snow surface, and the transmission coefficient for the vegetation canopy over the snowpack. Surface albedo is computed as a function of the number of days since the last snowfall and whether the snowpack is in an accumulation or a melt phase (U.S. Army, 1956). The transmission coefficient is computed as a function of the winter cover density of the vegetation canopy over the snowpack. The relations between cover density and the transmission coefficient were developed from relations presented by Miller (1959) and Vézina and Péch (1964).

Longwave net radiation is computed using the Stefan-Boltzmann law. The computation considers the longwave exchange between the air and the snowpack and the exchange between the vegetation canopy and the snowpack. Emissivity of the air is a function of the moisture content of the air and ranges between 0.757 and 1.0 (U.S. Army, 1956). In the absence of humidity data, air emissivity is assumed to be 1.0 for days with precipitation and a user-defined parameter for days without precipitation.

The full equation for computing latent and sensible heat flux includes terms for temperature, vapor pressure, wind speed, and diffusivities of heat and vapor (U.S. Army, 1956). However, wind and vapor pressure or humidity data are generally not available. Therefore, computation of the the latent and sensible heat terms is simplified to be a only a function of temperature and is computed only on days with precipitation. The computed value is reduced by one-half for HRUs with a cover-type of trees.

The snowpack is assumed to be a two-layered system. The surface layer consists of the upper 3-5 centimeters of the snowpack, and the bottom layer is the remaining snowpack. Heat transfer between the surface layer and the snowpack occurs by conduction when the temperature of the surface layer (Ts) is less than 0 ^{o}C. The conduction of heat between the surface and the snowpack is computed as a function of snowpack density, effective thermal conductivity, and the thermal gradient between the layers. Effective thermal conductivityis computed as a function of snowpack density (Anderson, 1968) and snowpack density is computed daily using a procedure developed by Riley et al. (1973). Conduction of heat from the soil surface to the snowpack is assumed to be negligible compared to the energy exchange at the air-snow interface.

When Ts equals 0 ^{o}C, heat transfer occurs as conduction when the net energy balance at the air-snow interface is negative; but heat transfer occurs as mass transfer by surface melting when the net energy balance is positive. Heat transfer from precipitation also occurs as a mass-transfer process. When snowmelt or rain-on-snow occur, the temperature of the snowpack controls the distribution of the melt.

If the snowpack temperature is less than 0 ^{o}C, the melt water is refrozen and decreases the cold content of the snowpack. When the snowpack becomes isothermal at 0 ^{o}C, snowmelt is first used to satisfy the freewater holding capacity of the snowpack. Any remaining melt leaves the bottom of the snowpack to become infiltration or surface runoff. When melt reduces the snowpack water equivalent below a user-defined threshold, the snowcovered area of an HRU is decreased using the areal-depletion-curve approach developed by Anderson (1973). Up to 10 different delpetion curves may be user-defined.

Evaporation and sublimation from the snow surface are assumed to occur only when there is no transpiration from vegetation above the snowpack. Loss from the snow surface is computed as a percentage of the daily PET value. The daily percentage is a user-defined parameter.

Channel Reservoir Components. There is no explicit routing of channel flow in PRMS daily mode. However, channel reservoir components can be used to simulate the storage and routing response of channel reservoirs [*strmflow_prms.f*]. Reservoir inflows are computed as the sum of the streamflow contributions from all HRU's and the parts of subsurface and ground-water reservoirs above the channel reservoir. Reservoir inflow also can include the outflow of up to three upstream channel reservoirs. Two types of routing procedures are available for simulating reservoir outflow. Both are based on the equation of continuity. One is a linear-storage routing procedure in which outflow is computed as a linear function of storage. The second is a modified-Puls routing procedure (U.S. Soil Conservation Service, 1971).

2. PRMS Storm Mode

A watershed is configured into flow-plane and channel segments for storm-mode computations. An HRU is considered a single flow plane. The watershed drainage network is characterized as a system of channel, reservoir, and junction segments that jointly describe the drainage pattern. Each channel segment can receive upstream inflow from as many as three other channel segments. In addition, each channel segment can receive lateral inflow from as many as two flow planes (left bank and right bank). The PRMS modules for storm mode are listed in Table 2.

Table 2. Storm mode process modules.

Process	**Module**	**Description**
Infiltration		
	grnampt_infil_prms.f	Green-Ampt infiltration
Flow-plane routing (flow and sediment)		
	krout_ofpl_prms.f	Kinematic overland-flow routing
Channel routing (flow, reservoirs, sediment)		
	krout_chan_prms.f	Kinematic channel-flow routing
Streamflow		
	strmflow_st_prms.f	Streamflow summation
Summary		
	basin_sum_st_prms.f	Basin summary computations

Surface Runoff. Storm precipitation is reduced by interception and resulting net precipitation is available for infiltration. On pervious areas, infiltration is computed using a variation of the Green and Ampt equation (Green and Ampt, 1911) [*grnampt_infil_prms.f*]. Point infiltration is converted to net infiltration over a flow plane using a procedure first presented by Crawford and Linsley (1966) which assumes that net infiltration at a given time step varies linearly as a function of the infiltration capacity and rainfall rate.

Rainfall excess (net precipitation less net infiltration) is then routed as surface runoff over the flow planes into the channel segments using the kinematic-wave approximation to overland flow developed by Leclerc and Schaake (1973) [*krout_ofpl_prms.f*].

Channel Flow. Channel flow is routed through the watershed channel system using the kinematic-wave approximation for channel flow described by Dawdy et al. (1978) [*krout_chan_prms.f*]. Routing through channel reservoirs can be computed using the same linear routing scheme or modified-Puls routing procedure available for the daily mode.

Sediment. Sediment detachment and transport from flow planes is computed using a rill-interrill concept approach presented by Hjelmfelt et al. (1975) [*krout_ofpl_prms.f*]. Rainfall detachment is computed as a nonlinear function of rainfall rate and the mean depth of flow on the plane using a relationship described by Smith (1976). Overland flow detachment is assumed to occur in the rills and is computed as a linear function of the difference between sediment transport capacity at the current flow depth and the current sediment transport rate using a relationship described by Hjelmfelt et al. (1975). Sediment delivered from a flow plane is currently transported as a conservative substance in the channel system; detachment and deposition are not included. Reports focusing on the sediment components of PRMS were presented by Carey and Simon (1984), Reed (1986), and Rankl (1987).

IV. MMS Analysis and Support Tools

A. Watershed Delineation and Parameter Estimation

The delineation, characterization, and parameterization of a basin and its associated HRUs can now be accomplished using geographic information system (GIS) technology. The GIS Weasel is a interface for applying tools to delineate, characterize, and parameterize topographical, hydrological, and biological basin features for use in a variety of lumped- and distributed-modeling approaches. It is composed of ArcInfo (ESRI, 1992) GIS software, C language programs, and shell scripts.

HRUs can be delineated within a watershed to reflect the variation in spatially distributed attributes, such as elevation, slope, aspect, soils, and vegetation. The GIS Weasel also delineates a drainage network and computes the connectivity of HRUs with this drainage network. The location of data-collection sites can also be overlaid with the HRU map to define associations between HRUs and the data sites.

Parameter estimation methods are implemented using ARC macro language (AML) functions. Keeping with the modular concept, a library of parameter estimation methods is maintained in a similar fashion to the library of process modules. For a given model, a recipe file of AML functions can be created and executed to estimate a selected set of spatial parameters. This recipe file can also be modified to change the parameter estimation method associated with a selected parameter, thus enabling the evaluation of alternative parameter estimation methods. Currently, methods to estimate selected spatially distributed model parameters have been developed for the USGS precipitation-runoff modelling system (PRMS) (Leavesley et al., 1983; Leavesley and Stannard, 1995) and TOPMODEL (Beven et al., 1995).

Digital databases used for parameter estimation in the USA include: (1) USGS digital elevation models; (2) State Soils Geographic (STATSGO) 1 km gridded soils data (US Department of Agriculture, 1994); and (3) Forest Service 1 km gridded vegetation type and density data (US Department of Agriculture, 1992). Spatially distributed parameters estimated using these databases include elevation, slope, aspect, topographic index, soil type, available water-holding capacity of the soil, vegetation type, vegetation cover density, solar radiation transmission coefficient, interception-storage capacity, stream topology, and stream reach slope and length.

B. Optimization and Sensitivity Analysis

Optimization and sensitivity analysis tools are provided to analyse model parameters and evaluate the extent to which uncertainty in model parameters affects uncertainty in simulation results. Two optimization procedures are available to fit user-selected parameters. One is the Rosenbrock technique (Rosenbrock, 1960), as it is implemented in the PRMS. The second is a hyper-tunnel method (Restrepo and Bras, 1982). The Shuffle Complex Evolution Optimization algorithm (Duan et al., 1993) and the Multi-Objective COMplex Evolution algorithm (Yapo et al., 1998), which is capable of solving multi-objective optimization problems, are currently being incorporated into the MMS tool set.

Two methods of sensitivity analysis are currently available. One is the method developed for use with the PRMS, which allows the evaluation of up to ten parameters at one time. The second method evaluates the sensitivity of any pair of parameters and develops the objective function surface for a selected range of these two parameters. To address the question of parameter and predictions uncertainty, the generalized likelihood uncertainty estimation (GLUE) procedure (Beven and Binley, 1992; Beven, 2001) is being added to the MMS tool set.

Spatially distributed parameters have an initial value assigned to each HRU, subsurface reservoir, or ground-water reservoir. Temporally distributed parameters have an initial value assigned for each time increment. One or any combination of parameters can be selected for optimization. For each iteration of a distributed parameter, all values of the parameter are moved in the same direction at the same time. The amount that each value is moved can be selected as the same magnitude or as the same percentage of the initial value. A major assumption in this fitting procedure is that the initial estimates of the values of a given distributed parameter are correct with regard to their relative differences in space or time.

An option in the fitting procedure allows the user to adjust different subsets of a distributed parameter independently. A special case of this option is that a distributed parameter may be adjuqted independently on all HRU's.

Sensitivity-analysis components allow the user to determine the extent to which uncertainty in the parameters results in uncertainty in the predicted runoff. When sensitivity analysis is coupled with optimization, the user also can assess the magnitude of parameter standard errors and parameter intercorrelations. Discussions of sensitivity analysis and its interpretation are presented by Mein and Brown (1978) and Beck and Arnold (1977).

Forecasting tools

Ensemble Streamflow Prediction (ESP)

The ESP procedure (Day, 1985) uses historic or synthesized meteorologic data as an analogue for the future. These time series are used as model input to simulate future streamflow. The initial hydrologic conditions of a watershed, for the start of a forecast period, are assumed to be those simulated by the model for that point in time. Typically, multiple hydrographs are simulated from this point in time forward, one for each year of available historic data. For each simulated hydrograph, the model is re-initialized using the watershed conditions at the starting point of the forecast period. The forecast period can vary from a few days to an entire water year. A frequency analysis is then performed on the peaks and/or volumes of the simulated hydrograph traces to evaluate their probabilities of exceedance. The ESP procedure uses historical meteorological data to represent future meteorological data. Alternative assumptions about future meteorological conditions can be made with the use of synthesized meteorological data.

A few options are available in applying the frequency analysis. One assumes that all years in the historic database have an equally likely probability of occurrence. This give equal weight to all years. Years associated with El Nino, La Nina, ENSO neutral, Pacific Decadal Oscillation (PDO) less than -0.5, PDO greater than 0.5, and PDO neutral have also been identified in the ESP procedure, and the years in these groups can be extracted separately for analysis. Alternative schemes for weighting user-defined periods, based on user assumptions or *a priori* information, are also being investigated.

Statistical downscaling.

Procedures to downscale atmospheric model output statistically for use as input to watershed models have been developed and coupled with the MMS (Wilby et al., 1999). These methods use a regression-based statistical downscaling model to simulate point values of daily precipitation and temperature from atmospheric-model output of grid-scale synoptic measures. The point estimates of climate variables are then spatially distributed across a basin using lapse rates and topographic information.

Climate generator

SYSTEM APPLICATIONS

Linking with other models

MMS provides a common framework in which to focus multidisciplinary research and operational efforts to provide improved understanding of complex water, energy, and biogeochemical processes. All the components of PRMS and ESP described above have been incorporated in MMS and the MMS modular library. Additional modules from a variety of other hydrologic and ecosystem models are currently being developed for incorporation into the modular library.

SYSTEM APPLICATIONS

The modeling system as discussed above has been applied in a variety of climatic and physiographic regions. Reports on snowmelt-runoff applications of PRMS include Leavesley and Striffler (1979), Leavesley et al. (1981), Brendecke and Sweeten (1985), and WMO (1986). A comparison of PRMS with the Streamflow Synthesis and Reservoir Regulation (SSARR) model was presented by Brendecke et al. (1985). A frozen soil algorithm was developed for PRMS by Emerson (1991) to simulate this cold-region process

PRMS was used in a number of studies to investigate the effects of surface coal mining on basin hydrologic response. A summary of these applications on approximately 50 basins in selected regions of the United States was presented by Stannard and Kuhn (1989). More recent applications of PRMS have been to address the potential effects of climate change on basin hydrologic response. Climate change related investigations in Colorado using PRMS coupled with selected atmospheric models were reported by Leavesley et al. (1992) and Hay et al. (1993). Application of selected storm-mode components, including sediment detachment and transport, to tephra deposits from the eruption of Mount St. Helens, Washington, were reported by Leavesley et al. (1989). Other reports focusing on the sediment components of PRMS were presented by Carey and Simon (1984), Reed (1986), and Rankl (1987).

Model parameter estimation and evaluation techniques have been examined by several authors. Parameter estimation and calibration studies were reported for Colorado (Norris and Parker, 1985) and for Montana and Wyoming (Cary, 1991). The transferability of parameters to noncalibrated bains was examined by Kuhn and Parker (1992). A review and application of the parameter optimization and sensitivity analysis components was presented by Troutman (1985). Error analysis methodology was also examined by Rivera-Santos (1990).

A number of approaches have been developed to use GIS tools in the delineation of HRUs for PRMS applications. Leavesley and Stannard (1990a,b) presented a polygon HRU approach while Battaglin et al. (1993) presented a gridded HRU approach. Leavesley and Stannard (1990a) also coupled remotely sensed snowcovered-area data with the GIS tools to provide the ability to compare measured and simulated snowcovered area on selected dates. Flügel and Lüllwitz (1993) developed GIS procedures to compare modeling of micro- and mesoscale catchments in the United States and Germany.

THE NEXT GENERATION OF PRMS

One of the objectives in the development of PRMS was to provide a modular modeling system that could be used to address a variety of interdisciplinary environmental and water-resource problems. The modular concept enables the testing and development of a variety of modeling approaches that can incorporate knowledge from a broad range of scientific disciplines. Assessment of the initial PRMS modular structure identified a number of deficiencies for meeting these goals, so a new, more flexible, modular system was developed to provide a framework in which PRMS, and any other model or model component, can be incorporated.

The new system is called the Modular Modeling System (MMS) (Leavesley et al., 1992). MMS is an integrated system of Unix-based computer software that has been developed to provide the research and operational framework needed to support development, testing, and evaluation of physical-process algorithms and to facilitate integration of user-selected sets of algorithms into operational physical-process models. MMS uses a master library that contains compatible modules for simulating a variety of water, energy, and biogeochemical processes. A model is created by selectively coupling the most appropriate process algorithms from the library to create an “optimal” model for the desired application. Where existing algorithms are not appropriate, new algorithms can be developed and incorporated in the library.

A geographic information system (GIS) interface has been developed for MMS to facilitate model development, application, and analysis. This interface permits application of a variety of GIS tools to characterize the topographic, hydrologic, and biologic features of a physical system for use in a variety of lumped- and distributed-parameter modeling approaches. MMS display capabilities permit visualization of the spatial distribution of model parameters and of the spatial and temporal variation of simulated state variables during a model run.

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