National Water Census
Water Availability and Use Science Program

Documentation of the Dynamic Parameter, Water-Use, Stream and Lake Flow Routing, and Two Summary Output Modules and Updates to Surface-Depression Storage Simulation and Initial Conditions Specification Options With the Precipitation-Runoff Modeling System (PRMS)

Chapter 8 of
Section B, Surface Water
Book 6, Modeling Techniques

Techniques and Methods 6–B8

U.S. Department of the Interior
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U.S. Geological Survey
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U.S. Geological Survey, Reston, Virginia: 2017

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Suggested citation:
Regan, R.S., and LaFontaine, J.H., 2017, Documentation of the dynamic parameter, water-use, stream and lake flow routing, and two summary output modules and updates to surface-depression storage simulation and initial conditions specification options with the Precipitation-Runoff Modeling System (PRMS): U.S. Geological Survey Techniques and Methods, book 6, chap. B8, 60 p., https://doi.org/10.3133/tm6B8.

ISSN 2328-7055 (online)

Preface

This report describes four modules and updates to two options for the Precipitation-Runoff Modeling System (PRMS) hydrologic simulation code. This report relies heavily upon information contained in Markstrom and others (2015), which documents the Precipitation-Runoff Modeling System, version 4. Summaries of changes to input and output values for PRMS are available on the Precipitation-Runoff Modeling System (PRMS) software distribution page (https://wwwbrr.cr.usgs.gov/projects/SW_MoWS/PRMS.html) by selecting “Changes in the specification of user inputs are reported as updates to tables in the Users’ Manual (tables 2, 1-2, 1-3, 1-5)” under Information. This report describes new Dynamic Parameter and Water-Use specification modules, a stream and lake-flow routing module, and two output summary modules, as well as updates to surface-depression storage simulation and initial conditions specification options as implemented in PRMS-V, version 5.0.0.

The performance of this software has been tested on several different computer systems and configurations. Future use, however, might reveal errors that were not detected during testing. Users are requested to notify the U.S. Geological Survey (USGS) of any errors found in this report or in the code, and submit questions by using the “Help” link at the top or “MoWS Contact Form” link found at the bottom of the Modeling of Watershed Systems (MoWS) web page at https://wwwbrr.cr.usgs.gov/projects/SW_MoWS/. Additionally, users can contact the USGS at

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Terminology

The following terms are used to reference components of the Precipitation-Runoff Modeling System (PRMS). See appendix 1 of U.S. Geological Survey Techniques and Methods, book 6, chapter B7 (Markstrom and others, 2015), for descriptions of modules, parameters, simulation algorithms, and computed variables for PRMS, version 4.

- PRMS is referred to as a hydrologic simulation code, whereas the associated input and output files and discretization are referred to as applications.
- Hydrologic response refers to the computed water storage and flow from and to the atmosphere, plant canopy, land surface, snowpack, surface depressions, shallow subsurface zone, deep aquifers, stream segments, and lakes.
- Parameter refers to preprocessed input values that characterize physical and topological attributes of the application domain and spatial and temporal computation coefficients of simulation algorithms.
- Dynamic parameters are time-varying parameters used to replace values of a parameter on a specified date.
- Flux variables are calculated flow rates.
- State variables are calculated water-content storages.
- Initial (or antecedent) conditions refer to states and fluxes required to initiate a simulation.

- An event is defined as a specified change in one or more dynamic parameter values and (or) water-use inputs on a specified date.
- Hydrologic Response Unit (HRU) refers to the primary spatial unit for which a PRMS application is discretized.
- Subbasins are user-specified groups of HRUs for which selected states and fluxes optionally can be computed.
- Reservoir refers to the conceptual water-storage capacity of each zone within an HRU, such as the capillary reservoir (CPR), groundwater reservoir (GWR), gravity reservoir (GVR), and preferential-flow reservoir (PFR) and not a surface-water body used for storage and regulation.
- Lake refers to any natural or artificial surface-water body used for storage and regulation of streamflow that is large enough to be simulated as a single or set of contiguous HRUs.

Font Styles

- Modules, filenames, and user input are identified by using Courier New font.
- Input parameters and dimensions are identified by using bold, Times New Roman font.
- State and flux variables are identified by using italic, Times New Roman font.

Abbreviations

ACFB	Apalachicola-Chattahoochee-Flint River Basin
CBH	Climate-by-HRU
cfs	cubic foot per second
CPR	capillary reservoir
CSV	comma-separated value
DPRST	surface-depression storage and flow simulation
ET	evapotranspiration
GDP	Geo Data Portal
GIS	geographic information system
GSFLOW	groundwater and surface-water flow model
GVR	gravity reservoir
GWR	groundwater reservoir
HRU	Hydrologic Response Unit
NHD	National Hydrography Dataset
PFR	preferential-flow reservoir
PRMS	Precipitation-Runoff Modeling System
PRMS-IV	Precipitation-Runoff Modeling System, Version 4

PRMS-V	Precipitation-Runoff Modeling System, Version 5
SWUDS	U.S. Geological Survey Site-Specific Water-Use Data System
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey

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Abstract

This report documents seven enhancements to the U.S. Geological Survey (USGS) Precipitation-Runoff Modeling System (PRMS) hydrologic simulation code: two time-series input options, two new output options, and three updates of existing capabilities. The enhancements are (1) new dynamic parameter module, (2) new water-use module, (3) new Hydrologic Response Unit (HRU) summary output module, (4) new basin variables summary output module, (5) new stream and lake flow-routing module, (6) update to surface-depression storage and flow simulation, and (7) update to the initial-conditions specification. This report relies heavily upon U.S. Geological Survey Techniques and Methods, book 6, chapter B7, which documents PRMS version 4 (PRMS-IV). A brief description of PRMS is included in this report.

Introduction

The availability, in terms of storage and timing, of water resources can be a limiting control on human and wildlife activities and ecological processes. Policymakers, natural resource managers, and the public have the need to assess the effects of historical, current, and projected land use, land cover, water use, and climate on the water resources on which they and ecosystems depend. Accounting for dynamic and evolving watershed characteristics within a single simulation may improve development and performance of hydrologic models for purposes of evaluating historical conditions or projecting possible future conditions. These changes can have natural and anthropogenic origins, for example: drought, fire, flooding, ecological succession, changing climate patterns, and water-resource management practices, such as transfers of water for agricultural use, consumptive use, urbanization, and flood mitigation. The U.S. Geological Survey (USGS) Precipitation-Runoff Modeling System, (Markstrom and others, 2015), hydrologic simulation code has been enhanced to account for these changes across spatial and temporal scales. Simulation results based on incorporating evolving watershed characteristics, climate change, and anthropogenic alterations may aid in the management of water resources and assessment of hydrologic processes, such as streamflow, surface-water storage, evapotranspiration, and snow melt.

Two new time-series input options are documented in this report: dynamic parameters and water use, which are included in PRMS-V. The dynamic parameter input option (module `dynamic_param_read`) provides the capability of varying several parameters that specify landscape and climate characteristics for each Hydrologic Response Unit (HRU; spatial units in PRMS). The water-use input option (module `water_use_read`) is used to specify the connectivity and flow rates of water transfers from water-supply sources to destination storage locations as a time series of values. The various water-use sources and destinations can be within and outside the model domain. Water-use information may be based on a wide range of water-resource management practices and scenarios for periods of years to centuries. Dynamic parameters and water-use information can be input on any day of the simulation time period.

With the new dynamic parameter and water-use options, models can be developed that can be used to evaluate various combinations of land-use and water-resource management practices to quantify possible effects on hydrologic processes and water availability prior to and after alterations of the natural system. Such simulations could possibly improve model calibration and validation and inform management decisions on local and regional scales. Examples of water-use practices that can be accounted for include diversion of water in stream segments and lakes; pumping from groundwater sources and surface-depression storage; and inter- and intra-basin transfers. Examples of projected scenarios that could be evaluated include changing agricultural practices that require pumping from aquifers and (or) streamflow diversions and consumptive-use requirements.

Two new output options are documented in this report and are included in PRMS-IV and PRMS-V. The `nhru_summary` module provides a method to produce output files, one for each user-selected variable of daily values for each modeled HRU. The `prms_summary` module provides a method to produce output files of daily values of select basin area-weighted variables. The output files for both modules are written in a comma-separated values (CSV) file format. The CSV format allows simulation results to be analyzed and visualized through direct input to many statistical and graphical software packages, such as Microsoft Excel, Google Spreadsheets, GNU R, and Math Works MATLAB. Additionally, these files could be used to generate input information required for other simulation codes, such as habitat, climate, hydraulic, lake operations, water-quality, and geochemical models for further simulations or scenario testing.

A new stream and lake flow-routing option (module `muskingum_lake`) and two updates to existing optional capabilities (surface-depression storage and initial-conditions specification) are documented in this report. The `muskingum_lake` module provides for streamflow routing using the Muskingum method (Linsley and others, 1982) and six lake flow-routing methods within a single simulation. This module was introduced in PRMS-V. Previous versions of PRMS assumed flow within stream segments to be inflow equals outflow when the lake flow-routing option (module `strmflow_lake`) was active. The `strmflow_lake` module is not included in PRMS-V. The simulation of surface depressions option is used to account for the possible effect of the aggregation of small, unregulated, surface-water storage features within any HRU. This option has been enhanced to include additional capabilities associated with flow computations, impervious areas, and closed depressions and for use with the dynamic parameter and water-use input options. The initial-conditions specification option is used to save computed variables at the conclusion of a simulation, referred to as a spin-up simulation, for use as initial (or antecedent) conditions for subsequent (or restart) simulations. This capability has been enhanced to provide new functionality and correct implementation errors of previous versions. The updates to surface-depression simulation and initial conditions specification are included in PRMS-IV and PRMS-V.

Technical information regarding input instructions and descriptions is presented in appendix 1; an example application is described in appendix 2. This report is not intended as instruction for derivation, application, or interpretation of dynamic parameters, water-use information, surface-depression storage, and lake hydrologic response within PRMS simulations.

Description of PRMS

The Precipitation-Runoff Modeling System (PRMS; Markstrom and others, 2015) is a modular, deterministic, distributed-parameter, physical-process-based hydrologic simulation code developed to evaluate effects of various combinations of climate, physical characteristics, and simulation options on hydrologic response and water distribution at the watershed scale. Previous versions of PRMS are documented in Markstrom and others (2008), Leavesley and others (1983, 1996, and 2005), and Leavesley and Stannard (1995). Figure 1 illustrates the hydrologic cycle as simulated by PRMS as a cross-sectional view perpendicular to a stream segment.

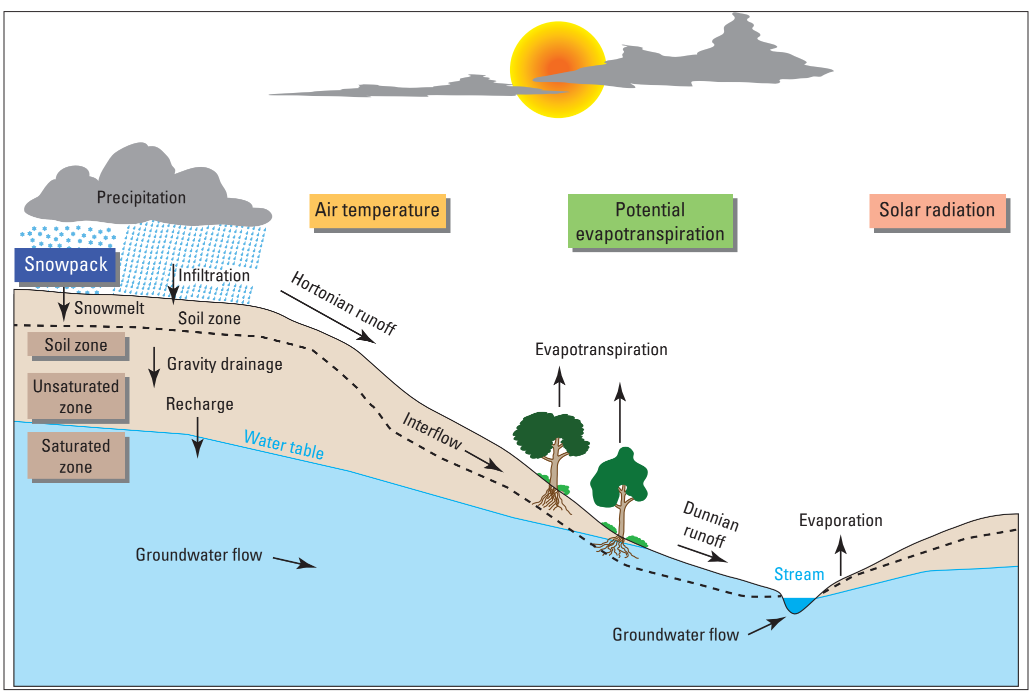

Figure 1. Diagram illustrating the hydrologic cycle as conceptualized in the Precipitation-Runoff Modeling System (modified from Markstrom and others, 2015).

PRMS is designed to

- simulate the full hydrologic cycle as determined by the energy and water budgets of the plant canopy, snowpack, and soil zone on the basis of distributed climate information (temperature, precipitation, and solar radiation),
- simulate hydrologic water budgets at the watershed scale for temporal scales ranging from days to centuries,
- accommodate application domains comprising single or multiple basins of any spatial discretization and size, such as 10s to 1,000s of square kilometers, regional, and continental,
- be computationally efficient (executions requiring seconds to minutes),
- use any spatial resolution of HRUs and stream segments,
- utilize commonly available physical and biological information to characterize and derive parameters used in the simulation algorithms, spatial discretization, and topological connectivity, and
- provide multiple options for computation of potential evapotranspiration, solar radiation, precipitation and temperature distribution, surface runoff, plant transpiration period (or growing season), streamflow, and lake storage and flow.

The modular programming structure allows the PRMS user community to develop and incorporate extensions as required for specific studies as parallel research and development efforts. For example, the addition of methods to account for dynamic parameters and incorporation of water-use and streamflow and lake routing algorithms, and the output of simulation results in new formats described in this report was facilitated by this modular design.

An application domain is discretized spatially into HRUs and stream segments. The goal of the discretization is to define a flow network that routes water from each HRU and stream segment to its downslope neighbors on the basis of flow direction, contributing area, and physical, anthropogenic, and biologic characteristics. Other discretization methods include use of a grid or an existing watershed discretization, such as the National Hydrography Dataset (NHD, https://nhd.usgs.gov/, and NHDPlus, http://www.horizon-systems.com/nhdplus/index.php). Any combination of discretization methods can be used. Individual HRUs and stream segments are assumed to be homogenous with respect to characteristics and hydrologic response. Flows to HRUs and stream segments are considered instantaneously mixed with any existing water storage. Simulation results can be evaluated at each HRU and stream segment and as groups of HRUs.

There are four HRU types: inactive, land, swale, and lake. Inactive HRUs represent areas within the application domain for which no computations are performed. Land and swale HRUs are conceptualized as a series of reservoirs that represent the storage capacity within the canopy, land surface (snowpack, impervious surfaces, and surface depressions), soil zone (capillary, gravity, and preferential flow), and groundwater reservoirs from which flows are computed. Swale HRUs are simulated identically to land HRUs except that lateral flows are not computed. Lake HRUs are conceptualized as the maximum areal extent of a surface-water body that includes a groundwater reservoir that can be connected to or separate from the stream network and adjacent HRUs. Figure 2 illustrates the hydrologic processes and water-storage reservoirs simulated for land HRUs, and figure 3 illustrates the hydrologic processes and water-storage reservoirs simulated in the soil zone for land HRUs. Figure 4 illustrates the hydrologic processes and water-storage reservoirs simulated for surface-depression storage.

Flow within and to stream segments can be routed or non-routed, replaced, and used for inflow to lakes, depending on values of various parameters specified in the Control and Parameter Files. Flow routing in the stream network is conceptualized as a single-direction, downslope sequence of stream segments, each of which are specified to flow into one or the other segment or be a terminus. Flowthrough segments can be routed as inflow equals outflow (`strmflow_in_out` module) or by using the Muskingum method (Linsley and others, 1982; Chow and others, 1988; `muskingum` and `muskingum_lake` modules). Individual flow rates for non-routed segments are not computed (`strmflow` module); the lateral inflows to the stream network are accumulated as total basin and optionally subbasin outflows. See Markstrom and others (2015) for descriptions of the `strmflow_in_out`, `muskingum`, and `strmflow` modules. A terminal segment does not flow to another segment and can either be a basin outlet or internal terminus such as to the land surface of an HRU representing a playa. The latter is accomplished by using the water-use input option (module `water_use_read`). A replaced stream segment is characterized as receiving inflow and generating outflow; however, the computed outflow in this case is not routed to a downstream segment, but rather is set to a specified measured streamflow included in the Data File. The use of replacement flows does not conserve mass, and typically replacement flows are used below controlled surface-water bodies (lakes or reservoirs) to account for management operations. A lake segment receives lateral flows from associated HRUs that are added to lake storage.

Dynamic Parameter Input Option—Module dynamic_param_read

Previous versions of PRMS required that all watershed characteristics and algorithm parameter values, typically

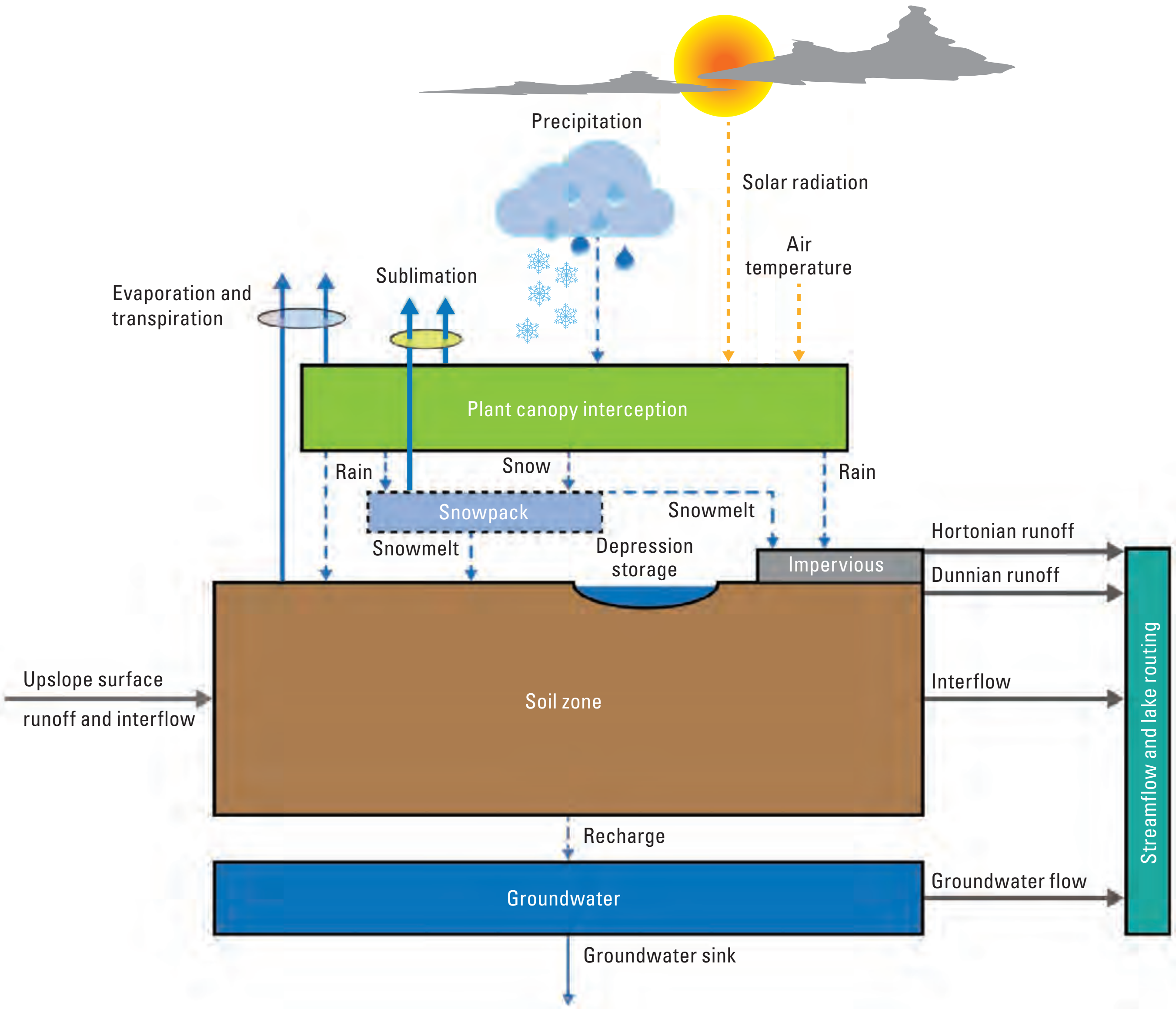

Figure 2. Schematic diagram illustrating the hydrologic processes for land Hydrologic Response Units (HRU) as conceptualized in the Precipitation-Runoff Modeling System. Dashed lines represent internal states; solid lines represent inflow and outflow. Swale HRUs are conceptualized the same as land HRUs except lateral flows (interflow, Hortonian runoff, or Dunnian runoff) are not produced.

derived from static, historical data sources, remain constant for the simulation time period—a static approach to model-domain parameterization. This approach can be insufficient to evaluate hydrologic responses when changes in landscape and climate are noteworthy over the simulation time period. Accounting for dynamic watershed characteristics may improve performance of hydrologic models and provide a method to evaluate possible effects of these changes on hydrologic processes, such as streamflow, evaporation, transpiration, runoff, infiltration, interflow, and water availability. This may be particularly important for models having time periods of decades and model domains that are regional and continental. Additionally, the use of dynamic parameters may influence the success of calibration efforts. The `dynamic_param_read` module was developed to provide this capability.

Milly and others (2008) discuss the problems with assuming static parameterization in climate-based modeling, stating that "stationarity is dead." Among the factors that support their hypothesis are increases and changes to human population distributions and the resultant landscape disturbances, increased water-use and pollutants, and natural cycles and anthropogenic-influenced hydroclimatic changes. These changes are "altering the means and extremes of precipitation, evapotranspiration, and rates of discharge of rivers" (Milly and others, 2008). Luo and others (2012) describe the effects of how conditional parameterization of a hydrologic model can lead to improved streamflow prediction. Van Beusekom and others (2014) demonstrate application of the PRMS dynamic parameter capability to evaluate the effects of changing land use and urbanization on streamflow in Puerto Rico between

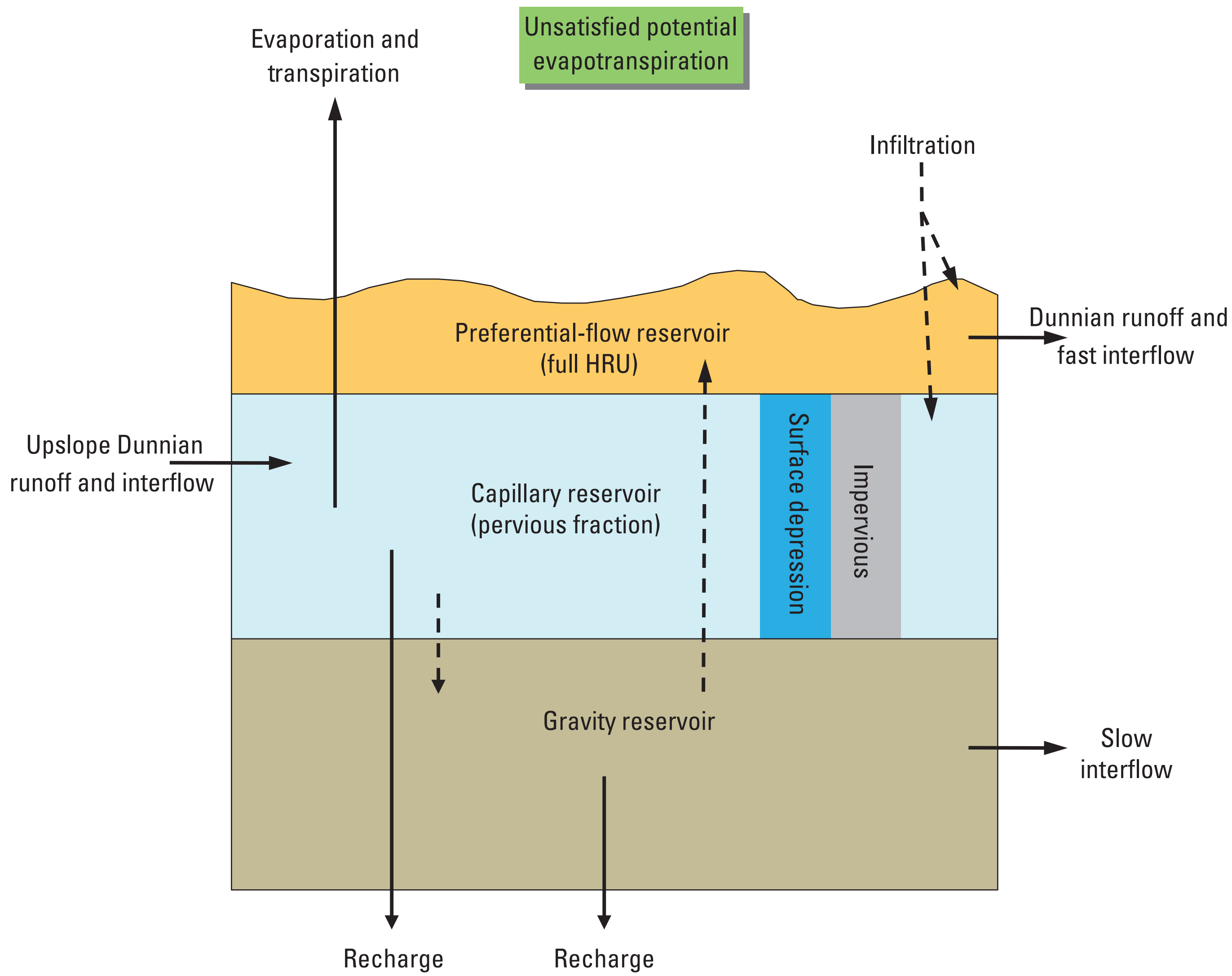

Figure 3. Schematic diagram illustrating the Precipitation-Runoff Modeling System soil zone of a land Hydrologic Response Unit. Dashed lines represent internal states; solid lines represent inflow and outflow. Inflow is the sum of throughfall, snowmelt, and upslope Hortonian runoff.

1952 and 2012. As part of that study, parameters related to impervious area and plant canopy were changed annually to validate the usefulness of dynamic parameters for watershed-scale hydrologic modeling. Similar dynamic parameters, including impervious area, plant canopy, and dynamic depression storage, were changed by LaFontaine and others (2015) to simulate projections of hydrologic response in the Apalachicola-Chattahoochee-Flint River Basin in the Southeastern United States through 2100.

Water-Use Input Option—Module water_use_read

Previous versions of PRMS had no means to represent constant or dynamically changing water transfers throughout a model domain or between water-storage locations, or to evaluate the effects of these transfers on hydrologic processes. The `water_use_read` module was developed to provide these capabilities. The module allows for specification of historical, current, and projected water-use information input as time series of water transfers based on water availability at storage locations internal and external to the model domain. For each transfer, the date, source, destination, and flow rate are specified. The date specifies the day on which the transfer is effective. The source and destination represent the spatial and temporal redistribution of water by human activities and natural processes. The flow rate remains constant for each time period between events for each source/destination pair.

Currently, water can be withdrawn from five sources: (1) stream segment flow, (2) groundwater reservoir storage, (3) open surface-depression storage, (4) external locations, and (5) lake storage. Source water can be transferred to any

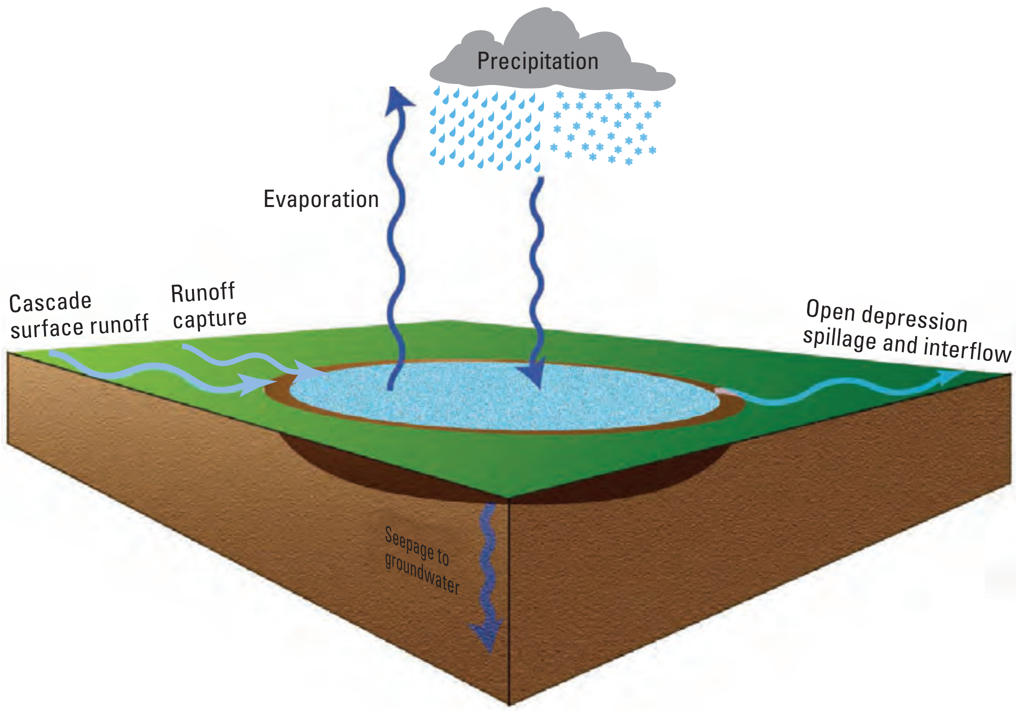

Figure 4. Schematic diagram illustrating the Precipitation-Runoff Modeling System surface-depression storage processes.

of eight destinations: (1) stream segments, (2) groundwater reservoir storage, (3) open surface-depression storage, (4) external locations, (5) lake storage, (6) capillary reservoir storage, (7) internal consumptive-use locations, and (8) plant canopy storage. Water transfers can be any source/destination combination. Multiple transfers can originate from each source, and each destination can receive water from multiple sources.

Specification of the water transfer connectivity between storage locations is analogous to specifying the water conveyance features within watersheds that may be the result of human activities and natural processes. The module could be used to account for naturally existing flows from, to, across, and under HRUs, application domain boundaries, and stream segments. Examples of water use include (a) diversion from stream segments to surface-depression storage; (b) withdrawal of groundwater storage applied to the plant canopy to approximate irrigation; (c) transbasin inflow from an external location; (d) consumptive use; and (e) streams terminating within an HRU, such as to a playa. Examples of projected scenarios that could be evaluated include changing agricultural practices that require pumping from aquifers and (or) streamflow diversions and consumptive-use requirements as population distributions change.

HRU Summary Output Option—Module nhru_summary

The `nhru_summary` module was developed to add the capability to write time-series files in a CSV format, named Nhru Summary Files, of daily, monthly, and (or) mean monthly values of user-selected variables with the number of values equal to the number of HRUs.

Basin Variables Summary Output Option—Module prms_summary

The `prms_summary` module was developed to add the capability to write time-series files in a CSV format, named PRMS Summary Files, of daily values of select basin-area average variables and optionally simulated streamflow for user-selected stream segments.

Stream and Lake Flow-Routing Option—Module muskingum_lake

Lake outflow and storage can be the most important component of the overall streamflow in a basin. Traditionally, accounting for lake hydrologic response in rainfall-runoff models has been ignored, because the primary focus of the simulation often is estimation of natural flows. Water-resource managers need methods to account for lake operation objectives. The PRMS methods of simulating lake hydrologic response are not intended for complex operations and rule-based, decision support, but provide rudimentary routing methods requiring minimal input and computation time to gain insight into lake hydrologic response.

The capability to simulate lake hydrologic response as initially implemented in PRMS is described by Dudley (2008).

An enhanced lake simulation capability, module strmflow_lake, is described in Markstrom and others (2015). The flow within the stream network for the strmflow_lake module is computed as “inflow equals outflow” for each stream segment. The module muskingum_lake was developed to add the capability to route flow in the stream network using the Muskingum flow-routing method (Linsley and others, 1982; Chow and others, 1988) with the simulation of lake hydrologic response. As with the strmflow_lake module, the muskingum_lake module provides six routing methods to account for regulated and unregulated lake outflow: (1) flowthrough, (2) linear, (3) modified Puls, (4) broad-crested weir, (5) gate-opening rating table, and (6) replacement flow that sets lake outflow to measured streamflow. Computed states and fluxes depend on the type of flow-routing method selected for each lake.

Surface-Depression Storage Simulation Option

The surface-depression storage and flow simulation (DPRST) option provides a method to account for possible hydrologic effects of unregulated, surface-water storage features that are too small to be discretized as individual water bodies. These features can be important controls on water availability and contribution to biologic activities, groundwater and surface-water interactions, storage and flow, wetland connectivity, and streamflow when the total surface-depression area is small relative to the watershed area. Surface depressions can be extensive enough that the aggregation of their water-holding capacity at the HRU scale is a substantial part of the hydrologic response and, thus, may need to be accounted for in a modeling study. See Steuer and Hunt (2001) for a discussion on including surface-depression storage and flow simulation in hydrologic modeling.

Typically, surface depressions provide for water storage during and immediately after precipitation and snowmelt events; however, some depressions may retain water for periods of months or year round. Some surface depressions occur naturally because of topographic and geologic features, such as prairie potholes, swales, and wetlands. Others can be ponds built for agriculture, livestock, mill work, or stormwater detention. Surface depressions can be geographically isolated (closed) from or connected (open) to the stream network. Each HRU can be specified to have both closed and open surface-depression storage components.

The DPRST option affects several aspects of the hydrologic cycle. Surface depressions capture throughfall, snowmelt, and a specified fraction of surface runoff generated within the HRU. DPRST water content is used to compute components of surface runoff, interflow, evaporation, and seepage to groundwater storage. Computations related to surface depressions are included in multiple modules, with the majority of computations in modules srunoff_carea and srunoff_smidx. The dynamic parameter and water-use input options can be used with the DPRST option, thus simulation of surface depressions could be used to investigate possible effects of historical and projected changes in surface depressions on water resources.

Simulation of surface-depression storage, as initially implemented in PRMS, is described by Vining (2002, 2004). Documentation of an enhanced surface-depression simulation implementation, as well as techniques for deriving required input information, including the delineation and attributes of surface depressions, is documented in Viger and others (2010). A more complete documentation of surface-depression simulation is described in Markstrom and others (2015). Documentation provided in this report supersedes documentation of the DPRST option provided in previous reports, though it does not provide information on techniques for deriving required input.

Initial-Conditions Specification Option

The persistence of water temporally and spatially (hydrologic memory) within a model domain is influenced by hydrogeologic and topographic characteristics and dynamic effects of climate, land, and water-use changes. The hydrologic conditions (model states at a point in time, such as soil zone, water body, and saturated-zone water content) can take years to decades to equilibrate with variable climatic conditions. Typically, surface-water hydrologic simulation codes set initial values for most states and fluxes to 0.0 with the option to specify some initial values, such as the water content of various components of the subsurface, snowpack, and outflow from stream segments. Simulation starting dates often are set to the first day of the water year[1] because this can be a day on which water content is at minimum values. These codes may assume that hydrologic memory throughout the model domain is adequately established within the first 3 years of a simulation time period with each simulated year requiring little execution time. The computed results for this initial, spin-up, time period often are disregarded. As hydrologic simulation applications expand to regional and national scales, however, values for initial states and fluxes can be difficult to estimate, a few years may not be adequate to account for hydrologic memory for all processes, such as groundwater storage, and each simulation year may require substantial execution time.

The capability to specify realistic hydrologic conditions for a particular date, that is, provide antecedent conditions, may improve and simplify evaluation of simulation results. The initial-conditions specification option provides this capability. It can be used to save to a file the hydrologic conditions for the last day of a spin-up simulation that are required to initiate any number of subsequent (or restart) simulations. Previous versions of PRMS provided an initial-conditions

[1]Water year is the period from October 1 to September 30 and is identified by the year in which the period ends.

specification option. The new implementation has been recoded to increase efficiency and flexibility and correct errors. The specification for writing and reading Initial Conditions Files is the same as previous versions. The content and format have changed, thus Initial Conditions Files generated by previous versions are not compatible with the current implementation. Part of the motivation for the redesign of the initial-conditions specification option is to provide this capability in the USGS coupled groundwater and surface-water flow model GSFLOW (Markstrom and others, 2008). Implementation in GSFLOW is documented in Regan and others (2015) in which this option is referred to as the restart option.

In general, PRMS simulations require little execution time (seconds to minutes per year), so the initial-conditions specification option is primarily intended for use with large application domains, calibration efforts, or GSFLOW applications. The use of Initial Conditions Files can substantially reduce the execution time and size of output files for a particular time period of interest, because the spin-up simulation time period is computed only once. Any number of restart simulations can use the values in a spin-up Initial Conditions File as antecedent conditions, with the restart date being the day after the spin-up simulation ended.

One use of the initial-conditions specification option is for forecasting hydrologic conditions. For example, a series of predictive simulations can be executed on the basis of ensembles of projected climate forecasts (that is, particular realizations of future conditions) with identical antecedent conditions previously computed for a selected date. This technique has been referred to as the extended streamflow prediction (ESP) procedure, which is included in the National Weather Service River Forecast System to compute short- and medium-range streamflow forecasts (Day, 1985). Another possible use of the initial-conditions specification option is in model calibration procedures that require identical antecedent conditions for 100s to 1,000s of calibration simulations.

Summary

This report documents enhancements to the Precipitation-Runoff Modeling System hydrologic simulation code as documented in Markstrom and others (2015). Five new modules are documented: (1) `dynamic_param_read`—the dynamic parameter input option, (2) `water_use_read`—the water-use input option, (3) `nhru_summary`—the Hydrologic Response Unit (HRU) summary output option, (4) `prms_summary`—the basin variables summary output option, and (5) `muskingum_lake`—simulation of streamflow routing using the Muskingum method with multiple options for simulation of lake dynamics. Additionally, enhancements to the simulation of surface-depression storage and use of Initial Conditions Files are documented.

The use of dynamic parameters and water-use information provides for inclusion of temporally and spatially varying watershed characteristics that can be used to evaluate historical, current, and projected land-use, water-use, storage capacities, and flow-routing scenarios. Spatial changes can be specified for any region or location within the model domain. Temporal changes can be specified on any day of a specified simulation time period. The results of such simulations can provide managers with a tool to assess potential effects of physical and climatic changes on hydrologic processes.

The primary objective for specification of water-use information is to provide a method to account for anthropogenic-driven water transfers from water-supply sources within and external to the model domain. Also, the information can be used to account for naturally existing flows from, to, across, and under HRUs and stream segments, such as can occur in areas with karst hydrogeologic features. Transfers can be routed to and from stream segments, groundwater storage, surface-depression storage, external locations, and lake storage. Additionally, transfers can be routed to consumptive-use locations and applied to soils and the plant canopy.

The new HRU and basin summary output options produce files in comma-separated values (CSV) format. This format allows simulation results to be analyzed and visualized through direct input to many statistical and graphical software packages. Additionally, these files can be used to generate input information required to loosely couple PRMS with other simulation codes.

Streamflow routing for models with on-channel lakes has been enhanced to provide for stream-segment routing using the Muskingum flow-routing method. In previous versions of PRMS, it was assumed that flow routing within stream segments was based solely on continuity, that is, inflow equals outflow for each segment when the lake flow-routing option was active.

The surface-depression storage option provides a method to account for the aggregate sum of small, unregulated, natural and constructed water bodies within each HRU. Inflow to surface depressions consists of rain throughfall and a specified fraction of surface runoff generated within the HRU. Outflows can be surface runoff, interflow, evaporation, and seepage to groundwater storage. Surface depressions in an HRU can be designated as open, closed, or a combination of both types. Closed surface depressions do not produce surface runoff or interflow. Information describing surface depressions can change dynamically within a simulation using the dynamic parameter input option, and water can be transferred to and from surface-depression storage using the water-use input option. The new implementation of the initial-conditions specification option has been redesigned to increase efficiency and flexibility and correct errors.

Acknowledgments

Support for these enhancements to PRMS was provided through the USGS National Research Program, the USGS National Water Census, the Water Availability and Use

Science Program, and the Southeast Regional Assessment Project (SERAP). Figures 2 and 4 were designed by Parker Norton of the USGS Dakota Water Science Center.

The reviewers of this manual were Rheannon Hart and Katherine Chase from the USGS Lower Mississippi Gulf and Montana Water Science Centers, respectively. The authors appreciate their thorough reviews and comments that greatly improved the quality of this manual.

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Appendixes

Appendix 1. Documentation of the Dynamic Parameter and Water-Use Input Options, Hydrologic Response Unit (HRU) and Basin Variables Summary Output Options, and Stream and Lake Flow-Routing, Surface-Depression Storage Simulation, and Initial-Conditions Specification Options

Appendix 2. PRMS Apalachicola-Chattahoochee-Flint River Basin Example Application to Demonstrate Use of Dynamic Parameters, Water-Use, Surface-Depression Storage, Streamflow With Lakes, NHRU Summary, and Initial-Conditions Capabilities

Appendix 1. Documentation of the Dynamic Parameter and Water-Use Input Options, Hydrologic Response Unit (HRU) and Basin Variables Summary Options, and Stream and Lake Flow-Routing, Surface-Depression Storage Simulation, and Initial-Conditions Specification Options

Introduction

This appendix documents five new Precipitation Runoff Modeling System (PRMS) modules: (1) `dynamic_param_read`—the dynamic parameter input option, (2) `water_use_read`—the water-use input option, (3) `nhru_summary`—the Hydrologic Response Unit (HRU) summary output option, (4) `prms_summary`—the basin variables summary output option, and (5) `muskingum_lake`-the stream and lake flow-routing option. Additionally, this appendix documents enhancements to simulation of surface-depression storage and initial-conditions specification options. Previous versions of PRMS are documented in Leavesley and others (1983, 1996, 2005), and Leavesley and Stannard (1995), and Markstrom and others (2008, 2015).

Dynamic Parameter Input Option—Module dynamic_param_read

To accommodate the input of temporally and spatially varying parameter values, a new module referred to as the dynamic parameter input option and named `dynamic_param_read` was developed. This module is used to update user-selected parameter values on any date of a simulation by using a time series of values. The values of these time-varying parameters, termed “dynamic parameters,” are used to replace previously specified values on a specified date and to adjust any associated model states, such as storage and areal extent, to maintain a water balance for each HRU. Dynamic parameter values could be used to account for changes in the model domain resulting from natural and anthropogenic origins, for example: drought, fire, flooding, ecological succession, changing climate patterns, and water-management practices. In previous versions of PRMS, all parameter values were held constant for the entire simulation time period.

The `dynamic_param_read` module provides the capability to evaluate historical, current, and projected changes and spatial trends in, and effects of, land-use and land-cover changes on hydrologic processes and response. Dynamic parameters include those that specify impervious surface fraction and storage capacity; storage capacity of the capillary and recharge reservoirs of the soil zone; total surface-depression storage and open surface-depression fractions, depth, pervious and impervious surface-runoff capture fraction, and storage threshold for open depressions to spill; canopy type, density, and storage capacity; plant transpiration period; and solar radiation transmission and potential evapotranspiration (ET) computation coefficients.

Sources of Dynamic Parameter Information

Sources of dynamic parameter values can be various combinations of historical, current, and projected watershed characteristics, climate calibration datasets, and flow-routing scenarios, such as time series of remotely sensed information and results from hydrologic, climate, and statistical models. One method to develop time-series of dynamic parameters is through the use of the U.S. Geological Survey (USGS) Geo Data Portal (GDP) (https://cida.usgs.gov/gdp/; accessed through Mozilla Firefox or Google Chrome) that provides access to climate, landscape, and geospatial information. A user of the GDP interface can supply a model domain as a pre-existing geographic information system (GIS) shapefile of the HRU discretization. The GDP includes several web-service processing algorithms; the user selects the dataset(s) and time period of interest and output file format (Blodgett, 2013). As the GDP project progresses, the catalog of data available through the portal is expected to expand.

Additional Input Files for Use of the Dynamic Parameter Input Option

The `dynamic_param_read` module reads time series of values for each HRU from new input files, named Dynamic Parameter Files. Separate files are used for each dynamic parameter. The time period and frequency can differ between Dynamic Parameter Files. The time series of values can be input using regular and irregular intervals, provided the values are in chronological order. Each entry (the effective start date) in the Dynamic Parameter Files is termed an “event,” which can be specified for any date within or outside of a specified simulation time period. Only events that occur within the selected simulation time period are used; any additional events specified before or after the simulation period are ignored.

Specifications for Use of the Dynamic Parameter Input Option

The dynamic parameter input option is activated by using any of 13 control parameter flags (table 1-1) specified in the Control File. For each dynamic parameter type, two control parameters are specified: (1) a flag to activate or deactivate use of a dynamic parameter and (2) the Dynamic Parameter File pathname. Specifying a value greater than 0 for a flag indicates that one or more Dynamic Parameter Files are input and that each specifies one of the dynamic parameters (table 1-2). Control parameter flags **dyn_covden_flag**, **dyn_dprst_flag**,

dyn_imperv_flag, **dyn_intcp_flag**, **dyn_potet_flag**, **dyn_soil_flag**, and **dyn_transp_flag** can be specified as combinations for a dynamic parameter type. For example, a value of 1 for control parameter **dyn_imperv_flag** indicates that values of **hru_percent_imperv** are specified in Dynamic Parameter File **imperv_frac_dynamic**; a value of 2 indicates that values of **imperv_stor_max** are specified in Dynamic Parameter File **imperv_stor_dynamic**; and a value of 3 indicates that values of **hru_percent_imperv** and **imperv_stor_max** are specified in Dynamic Parameter Files **imperv_frac_dynamic** and **imperv_stor_dynamic**, respectively. The pathname of the Dynamic Parameter Files are specified using an associated control parameter. See appendix 1 of Markstrom and others (2015) for a description of the Control File and Parameter File and the hydrologic processes associated with dynamic parameters. The 20 parameters that can be dynamically updated are:

- two impervious area parameters: (1) **hru_percent_imperv** and (2) **imperv_stor_max**;
- four surface-depression storage parameters: (1) **dprst_frac**, (2) **dprst_depth_avg**, (3) **sro_to_dprst_perv**, and (4) **sro_to_dprst_imperv**;
- six canopy parameters: (1) **cov_type**, (2) **wrain_intcp**, (3) **srain_intcp**, (4) **snow_intcp**, (5) **covden_sum**, and (6) **covden_win**;
- four plant transpiration (growing season) parameters: (1) **transp_beg**, (2) **transp_end**, (3) **spring_frost**, and (4) **fall_frost**;
- one potential ET parameter (***potet_coef***), which is the generic name of a parameter required by the active ET module: **jh_coef** and **jh_coef_hru**, **pt_alpha**, **hs_krs**, **hamon_coef**, **epan_coef**, **potet_cbh_adj**, or **pm_n_coef** and **pm_d_coef** used in `potet_jh`, `potet_pt`, `potet_hs`, `potet_hamon`, `potet_pan`, `climate_hru`, and `potet_pm` modules, respectively;
- two soil-zone storage parameters: (1) **soil_moist_max** and (2) **soil_rechr_max_frac**; and
- a solar radiation transmission parameter: **rad_trncf**.

Specifying a value greater than `0` for a dynamic parameter control flag (table 1–1) indicates that one or more Dynamic Parameter Files are input and that each specifies one of the dynamic parameters (table 1–2). The 13 control parameter flags and associated parameters and conditions specified for each dynamic parameter are

1. **dyn_imperv_flag**—events related to impervious surfaces: when specified equal to `1` or `3` the areal proportion parameter (**hru_percent_imperv**) values are read from the file specified by using control parameter **imperv_frac_dynamic**; when specified equal to `2` or `3` the storage-capacity parameter (**imperv_stor_max**) values are read from the file specified by using control parameter **imperv_stor_dynamic**.
2. **dyn_dprst_flag**—events related to surface-depression storage: when specified equal to `1` or `3` the areal proportion parameter (**dprst_frac**) values are read from the file specified by using control parameter **dprst_frac_dynamic**; when specified equal to `2` or `3` the average depth parameter (**dprst_depth_avg**) values are read from the file specified by using control parameter **dprst_depth_dynamic**.
3. **dyn_sro2dprst_perv_flag**—when specified equal to `1`, events related to the portion of surface runoff from pervious areas captured by surface-depression storage parameter (**sro_to_dprst_perv**) values are read from the file specified by using control parameter **sro2dprst_perv_dynamic**.
4. **dyn_sro2dprst_imperv_flag**—when specified equal to `1`, events related to the portion of surface runoff from impervious areas captured by surface-depression storage parameter (**sro_to_dprst_imperv**) values are read from the file specified by using control parameter **sro2dprst_imperv_dynamic**.
5. **dyn_covtype_flag**—when specified equal to `1`, events related to the canopy cover type parameter (**cov_type**) values are read from the file specified by using control parameter **covtype_dynamic**.
6. **dyn_covden_flag**—events related to canopy cover density: when specified equal to `1` or `3` the summer canopy-cover density parameter (**covden_sum**) values are read from the file specified by using control parameter **covden_sum_dynamic**; when specified equal to `2` or `3` the winter canopy-cover density parameter (**covden_win**) values are read from the file specified by using control parameter **covden_win_dynamic**.
7. **dyn_intcp_flag**—events related to canopy-interception storage: when specified equal to `1`, `3`, `5`, or `7` the winter canopy-interception storage parameter (**wrain_intcp**) values are read from the file specified by using control parameter **wrain_intcp_dynamic**; when specified equal to `2`, `3`, `6`, or `7` the summer canopy-interception storage parameter (**srain_intcp**) values are read from the file specified by using control parameter **srain_intcp_dynamic**; when specified equal to `4`, `5`, `6`, or `7` the snow canopy-interception storage parameter (**snow_intcp**) values are read from the file specified by using control parameter **snow_intcp_dynamic**.
8. **dyn_transp_flag**—events related to transpiration period using `transp_tindex` module: when specified equal to `1` or `3` the transpiration beginning month parameter (**transp_beg**) values are read from the file specified by using control parameter **transpbeg_dynamic**; when

specified equal to `2` or `3` the transpiration ending month parameter (**transp_end**) values are read from the file specified by using control parameter **transpend_dynamic**.

9. **dyn_soil_flag**—events related to storage capacity of the capillary reservoir: when specified equal to `1` or `3` the maximum storage capacity parameter (**soil_moist_max**) values are read from the file specified by using control parameter **soilmoist_dynamic**; when specified equal to `2` or `3` the storage capacity of the recharge zone parameter (**soil_rechr_max_frac**) values are read from the file specified by using control parameter **soilrechr_dynamic**.

10. **dyn_radtrncf_flag**—when specified equal to `1`, events related to the solar radiation transmission coefficient parameter (**rad_trncf**) values are read from the file specified by using control parameter **radtrncf_dynamic**.

11. **dyn_potet_flag**—events related to potential evapotranspiration coefficients: when specified equal to `1` or `2` values for a parameter, generically referred to as ***potet_coef***, which is associated with the active potential ET module (control parameter **et_module**), values are read from the file specified by using control parameter **potetcoef_dynamic**. When control parameter **dyn_potet_flag** is specified with the value `1`, one of parameters **jh_coef**, **pt_alpha**, **hs_krs**, **hamon_coef**, **epan_coef**, **potet_cbh_adj**, or **pm_n_coef** is read for modules `potet_jh`, `potet_pt`, `potet_hs`, `potet_hamon`, `potet_pan`, `climate_hru`, and `potet_pm`, respectively. When **dyn_potet_flag** is specified with the value `2`, one of parameters **jh_coef_hru** or **pm_d_coef** is read for modules `potet_jh` and `potet_pm`, respectively. The specified values are used to assign values to the month for the date on which the event occurs.

12. **dyn_fallfrost_flag**—events related to transpiration period using `transp_frost` module: when specified equal to `1`, the transpiration ending Julian Day parameter (**fall_frost**) values are read from the file specified by using control parameter **fallfrost_dynamic**.

13. **dyn_springfrost_flag**—events related to transpiration period using `transp_frost` module: when specified equal to `1`, the transpiration beginning Julian Day parameter (**spring_frost**) values are read from the file specified by using control parameter **springfrost_dynamic**.

Specification of the Dynamic Parameters

All initial parameter values are specified in the Parameter File(s) and remain constant during a simulation time period unless updated by using Dynamic Parameter Files. Dynamic parameter values are held constant from the simulation start date until any event, at which time the values are updated and held constant until any subsequent event. Interpolations between events are not computed; thus, specified events for each dynamic parameter need to be of fine enough temporal resolution to represent the landscape and (or) hydroclimatic changes that minimize any discontinuity effect on related hydrologic processes and goals of the study. For each day on which one or more of the dynamic parameters change, a value is specified for each HRU. Any associated model states, such as storage, that were computed on the basis of the previous values of a dynamic parameter are adjusted to conserve mass on the day of the event.

There are two options for specifying values for each day on which one or more of the dynamic parameters changes: (1) a valid replacement value is specified for each HRU or (2) a valid replacement value is specified for each HRU that has changed and the value "`-1`" is specified to indicate retention of the previous value for those HRUs (that is the value has not changed for this event). Typically, option 1 would be used because the derivation of the replacement parameter values could be identical to the derivation of the initial parameter values. The second option might be used to facilitate visual identification within the Dynamic Parameter Files of those HRUs where changes were noteworthy. As values of parameter **jh_coef_hru**, which can be specified when **et_module** is specified equal to `potet_jh`, can be negative, all values for this parameter must be specified; thus, the `-1` retention flag cannot be used for this parameter. If the source of dynamic parameter values has a smaller areal extent than the model domain, specify the value `-1` for HRUs outside the areal extent of the dynamic parameter data source. For example, option 2 could assist users to evaluate the change in the amount of impervious area for only a few HRUs.

The time series of events are specified in time order in each file as the event date and values for each HRU, in order, from HRU with identification 1 to the last HRU with the identification number equal to the number of HRUs (dimension **nhru**). Any number of events can be specified in a Dynamic Parameter File. The input values that are specified on each data line of a Dynamic Parameter File are defined in table 1–3.

Figure 1–1 provides an example Dynamic Parameter File. This example specifies four impervious fraction events for a model with seven HRUs. Note: A `-1` value is specified for several HRU values to indicate that the value for those HRUs did not change for the event. Specified parameter values will be integer or real depending on the parameter data type. Any number of spaces can be used between values, and an event can be specified over multiple lines, which can be convenient for a grid-based HRU delineation. Lines preceding the line that begins with four "#" characters are ignored; thus, any number of comment lines can be used to describe the values, such as the data source, model run, etc.

Table 1–1. Input control parameters to the Dynamic Parameter Module—dynamic_param_read.

[HRU, hydrologic response unit; ET, evapotranspiration]

Parameter name	Description	Condition	Type	Range	Default
covden_sum_dynamic	Pathname of the time series of pre-processed values for summer plant-cover density used to set values of **covden_sum** for each HRU	**dyn_covden_flag** = 1 or 3	character	user defined	dyncovsum
covden_win_dynamic	Pathname of the time series of pre-processed values for winter plant-cover density used to set values of **covden_win** for each HRU	**dyn_covden_flag** = 2 or 3	character	user defined	dyncovwin
covtype_dynamic	Pathname of the time series of pre-processed values used to set values of **cov_type** for each HRU	**dyn_covtype_flag =** 1	character	user defined	dyncovtype
dprst_depth_dynamic	Pathname of the time series of pre-processed values used to set values of **dprst_depth_avg**	**dyn_dprst_flag** = 2 or 3	character	user defined	dyndprst_depth
dprst_frac_dynamic	Pathname of the time series of pre-processed values used to set values of **dprst_frac**	**dyn_dprst_flag =** 1 or 3	character	user defined	dyndprst_frac
dyn_covden_flag	Flag to indicate if a time series of plant-canopy density values are input in a Dynamic Parameter File(s) (0=no; 1=file **covden_sum_dynamic**; 2=file **covden_win_dynamic**; 3=both)	dynamic canopy cover density	integer	0 to 3	0
dyn_covtype_flag	Flag to indicate if a time series of plant-canopy type values are input in Dynamic Parameter File **covtype_dynamic** (0=no; 1=yes)	dynamic canopy cover type	integer	0 or 1	0
dyn_dprst_flag	Flag to indicate if a time series of surface-depression values are input in a Dynamic Parameter File(s) (0=no; 1=file **dprst_frac_dynamic**; 2=file **dprst_depth_dynamic**; 3=both)	dynamic surface depression	integer	0 to 3	0
dyn_fallfrost_flag	Flag to indicate if a time series of transpiration start Julian day values are input in a Dynamic Parameter File(s) (0=no; 1 =file **fallfrost_dynamic**)	dynamic transpiration and transp_module = `transp_frost`	integer	0 or 1	0
dyn_imperv_flag	Flag to indicate if a time series of impervious values are input in a Dynamic Parameter File(s) (0=no; 1=file **imperv_frac_dynamic**; 2=file **imperv_stor_dynamic**; 3=both)	dynamic impervious	integer	0 to 3	0
dyn_intcp_flag	Flag to indicate if a time series of plant canopy interception values are input in a Dynamic Parameter File(s) (0=no; 1=file **wrain_intcp_dynamic**; 2=file **srain_intcp_dynamic**; 4=file **snow_intcp_dynamic**; additive combinations)	dynamic interception	integer	0 to 7	0

Table 1–1. Input control parameters to the Dynamic Parameter Module—dynamic_param_read.—Continued

[HRU, hydrologic response unit; ET, evapotranspiration]

Parameter name	Description	Condition	Type	Range	Default
dyn_potet_flag	Flag to indicate if a time series of potential ET coefficient values are input in Dynamic Parameter File **potetcoef_dynamic** to update coefficients for the specified month for the selected potential ET module specified by control parameter **et_module** (0=no; 1=parameter **jh_coef**, **pt_alpha**, **hs_krs**, **hamon_coef**, **epan_coef**, **potet_cbh_adj**, and **pm_n_coef** used in potet_jh, potet_pt, potet_hs, potet_hamon, `potet_pan`, `climate_hru`, and `potet_pm modules`, respectively; 2= parameter **jh_coef_hru**, **pm_d_coef** used in `potet_jh` and `potet_pm` modules, respectively)	dynamic potential ET	integer	0 to 2	0
dyn_radtrncf_flag	Flag to indicate if a time series of solar radiation values are input in Dynamic Parameter File **radtrncf_dynamic** (0=no; 1=yes)	dynamic transmission	integer	0 or 1	0
dyn_soil_flag	Flag to indicate if a time series of soil-water capacity values are input in a Dynamic Parameter File(s) (0=no; 1=file **soilmoist_dynamic** only, 2=file **soilrechr_dynamic** only; 3=both)	dynamic soil moisture	integer	0 to 3	0
dyn_springfrost_flag	Flag to indicate if a time series of transpiration start Julian day values are input in a Dynamic Parameter File(s) (0=no; 1 =file **springfrost_dynamic**)	dynamic transpiration and transp_module = `transp_frost`	integer	0 or 1	0
dyn_sro2dprst_perv_flag	Flag to indicate if a time series of fraction of surface runoff from the pervious portion of an HRU are input in Dynamic Parameter File **sro2dprst_perv_dyn** (0=no; 1=yes)	dynamic surface depression	integer	0 or 1	0
dyn_sro2dprst_imperv_flag	Flag to indicate if a time series of fraction of surface runoff from the impervious portion of an HRU are input in Dynamic Parameter File **sro2dprst_imperv_dynamic** (0=no; 1=yes)	dynamic surface depression	integer	0 or 1	0
dyn_transp_flag	Flag to indicate if a time series of transpiration month values are input in a Dynamic Parameter File(s) (0=no; 1=file **transpbeg_dynamic**; 2=file **transpend_dynamic** only, 3=both)	dynamic transpiration and transp_module = `transp_tindex`	integer	0 to 3	0
et_module	Module name for potential ET method	required	character	`climate_hru`, `potet_jh`, `potet_hamon`, `potet_hs`,`potet_pt`, `potet_pm`, or `potet_pan`	potet_jh

Table 1–1. Input control parameters to the Dynamic Parameter Module—dynamic_param_read.—Continued

[HRU, hydrologic response unit; ET, evapotranspiration]

Parameter name	Description	Condition	Type	Range	Default
fallfrost_dynamic	Pathname of the time series of pre-processed values for dynamic parameter **fall_frost**	**dyn_fallfrost_flag** = 1 and transp_module = `transp_frost`	character	user defined	dynfallfrost
imperv_frac_dynamic	Pathname of the time series of pre-processed values for dynamic parameter **imperv_frac**	**dyn_imperv_flag** = 1 or 3	character	user defined	dynimperv
imperv_stor_dynamic	Pathname of the time series of pre-processed values for dynamic parameter **imperv_stor_max**	**dyn_imperv_flag** = 2 or 3	character	user defined	dynimperv
potet_coef_dynamic	Pathname of the time series of pre-processed potential evapotranspiration coefficient values where the parameter is dependent on the value of **et_module**	**dyn_potet_flag** = 1 or 2	character	user defined	dynpotetcoef
radtrncf_dynamic	Pathname of the time series of pre-processed values for dynamic parameter **rad_trncf**	**dyn_radtrncf_flag** = 1	character	user defined	dynradtrncf
snow_intcp_dynamic	Pathname of the time series of pre-processed values for dynamic parameter **snow_intcp**	**dyn_intcp_flag** = 4, 5, 6, or 7	character	user defined	dynsnowintcp
soilmoist_dynamic	Pathname of the time series of pre-processed values for dynamic parameter soil_moist_max	**dyn_soil_flag** = 1 or 3	character	user defined	dynsoilmoist
soilrechr_dynamic	Pathname of the time series of pre-processed values for dynamic parameter **soil_rechr_max_frac**	**dyn_soil_flag** = 2 or 3	character	user defined	dynsoilrechr
springfrost_dynamic	Pathname of the time series of pre-processed values for dynamic parameter **spring_frost**	**dyn_springfrost_flag** = 1 and transp_module = `transp_frost`	character	user defined	dynspringfrost
srain_intcp_dynamic	Pathname of the time series of pre-processed values for dynamic parameter **srain_intcp**	**dyn_intcp_flag** = 2, 3, 6, or 7	character	user defined	dynsrainintcp
sro2dprst_perv_dynamic	Pathname of the time series of pre-processed values for dynamic parameter **sro_to_dprst_perv**	**dyn_sro2dprst_perv_flag** = 1	character	user defined	dynsrotodprst_perv
sro2dprst_imperv_dynamic	Pathname of the time series of pre-processed values for dynamic parameter **sro_to_dprst_imperv**	**dyn_sro2dprst_imperv_flag** = 1	character	user defined	dynsrotodprst_imperv
transpbeg_dynamic	Pathname of the time series of pre-processed values for dynamic parameter **transp_beg**	**dyn_transp_flag** = 1 or 3 and transp_module = `transp_tindex`	character	user defined	dyntranspbeg
transpend_dynamic	Pathname of the time series of pre-processed values for dynamic parameter **transp_end**	**dyn_transp_flag** = 2 or 3 and transp_module = `transp_tindex`	character	user defined	dyntranspend
wrain_intcp_dynamic	Pathname of the time series of pre-processed values for dynamic parameter **wrain_intcp**	**dyn_intcp_flag** = 1, 3, 5, or 7	character	user defined	dynwrainintcp

Table 1–2. Input dynamic parameters to the Dynamic Parameter Module—dynamic_param_read.

[HRU, hydrologic response unit; **nhru**, number of HRUs; **nmonths**, constant number equal to 12; temp_units, flag to indicate the units of measured air-temperature values (0=Fahrenheit; 1=Celsius)]

Parameter name	Description	Condition	Dimension	Type	Unit	Range	Default
cov_type	Vegetation cover typefor each HRU (0=bare soil; 1=grasses; 2=shrubs; 3=trees; 4=coniferous)	**dyn_covtype_flag** = 1	**nhru**	integer	none	0 to 4	3
covden_sum	Summer vegetation cover density for the major vegetation type in each HRU	**dyn_covden_flag** = 1 or 3	**nhru**	real	decimal fraction	0.0 to 1.0	0.5
covden_win	Winter vegetation cover density for the major vegetation type in each HRU	**dyn_covden_flag** = 2 or 3	**nhru**	real	decimal fraction	0.0 to 1.0	0.5
dprst_depth_avg	Average depth of storage depressions at maximum storage capacity	**dyn_dprst_flag** = 2, 3, 6, or 7 and **dprst_flag** = 1	**nhru**	real	inches	0.0 to 500.0	132.0
dprst_frac	Fraction of each HRU area that has surface depressions	**dyn_dprst_flag** = 1, 3, 5, or 7 and **dprst_flag** = 1	**nhru**	real	decimal fraction	0.0 to 1.0	0.0
fall_frost	The solar date (number of days after winter solstice) of the first killing frost of the fall	**dyn_fallfrost_flag** = 1 and **transp_module** = `transp_frost`	**nhru**	integer	solar date	1 to 366	264
hru_percent_imperv	Fraction of each HRU area that is impervious	**dyn_imperv_flag** = 1 or 3	**nhru**	real	decimal fraction	0.0 to 0.999	0.0
imperv_stor_max	Maximum impervious area retention storage for each HRU	**dyn_imperv_flag** = 2 or 3	**nhru**	real	inches	0.0 to 0.1	0.05
potet_coef[1]	Monthly (January to December) potential ET coefficient for each HRU used by the selected potential ET module as specified by control parameter **et_module**	**dyn_potet_flag** = 1 or 2	**nhru**, **months**	real	varies	varies	varies
rad_trncf	Transmission coefficient for short-wave radiation through the winter vegetation canopy	**dyn_radtrncf_flag** = 1	**nhru**	real	decimal fraction	0.0 to 1.0	0.5
soil_moist_max	Maximum available water holding capacity of capillary reservoir from land surface to rooting depth of the major vegetation type of each HRU	**dyn_soil_flag** = 1 or 3	**nhru**	real	inches	0.00001 to 10.0	2.0
soil_rechr_max_frac	Maximum storage for soil recharge zone (upper portion of capillary reservoir where losses occur as both evaporation and transpiration) as a fraction of **soil_moist_max**	**dyn_soil_flag** = 2 or 3	**nhru**	real	decimal fraction	0.00001 to 1.0	1.0
snow_intcp	Snow interception storage capacity for the major vegetation type in each HRU	**dyn_intcp_flag** = 3, 5, 6, or 7	**nhru**	real	inches	0.0 to 1.0	0.1
spring_frost	The solar date (number of days after winter solstice) of the last killing frost of the spring	**dyn_springfrost_flag** = 1 and **transp_module** = `transp_frost`	**nhru**	integer	solar day	1 to 366	111

Table 1–2. Input dynamic parameters to the Dynamic Parameter Module—dynamic_param_read.—Continued

[HRU, hydrologic response unit; **nhru**, number of HRUs; **nmonths**, constant number equal to 12; temp_units, flag to indicate the units of measured air-temperature values (0=Fahrenheit; 1=Celsius)]

Parameter name	Description	Condition	Dimension	Type	Unit	Range	Default
srain_intcp	Summer rain interception storage capacity for the major vegetation type in each HRU	**dyn_intcp_flag** = 2, 4, 6, or 7	**nhru**	real	inches	0.0 to 1.0	0.1
sro_to_dprst_perv	Fraction of pervious surface runoff that flows into surface depression storage; the remainder flows to a stream network for each HRU	**dyn_sro2dprst_perv_flag** = 1 and **dprst_flag** = 1	**nhru**	real	decimal fraction	0.0 to 1.0	0.2
sro_to_dprst_imperv	Fraction of impervious surface runoff that flows into surface depression storage; the remainder flows to a stream network for each HRU	**dyn_sro2dprst_imperv_flag** = 1 and **dprst_flag** = 1	**nhru**	real	decimal fraction	0.0 to 1.0	0.2
transp_beg	Month to begin summing maximum air temperature for each HRU; when sum is greater than or equal to **transp_tmax**, transpiration begins	**dyn_transp_flag** = 1 or 3 and **transp_module** = `transp_tindex`	**nhru**	integer	month	1 to 12	1
transp_end	Month to stop transpiration computations; transpiration is computed thru end of previous month	**dyn_transp_flag** = 2 or 3 and transp_module = `transp_tindex`	**nhru**	integer	month	1 to 13	13
transp_tmax	Temperature index to determine the specific date of the start of the transpiration period; the maximum air temperature for each HRU is summed starting with the first day of month transp_beg; when the sum exceeds this index, transpiration begins	**transp_module** = `transp_tindex`	**nhru**	real	temp_units	1.0 to 1000.0	1.0
wrain_intcp	Winter rain interception storage capacity for the major vegetation type in each HRU	**dyn_intcp_flag** = 1, 3, 5, or 7	**nhru**	real	inches	0.0 to 1.0	0.1

Table 1–3. Input values specified in Dynamic Parameter Files for each event for the Dynamic Parameter Module—dynamic_param_read.

[HRU, hydrologic response unit; --, values depend on dynamic parameter specified]

Value	Description	Type	Unit	Range
year	Year of the date when the dynamic parameter event begins	integer	year	user defined
month	Month of the date when the dynamic parameter event begins	integer	month	user defined
day	Day of the date when the dynamic parameter event begins	integer	day	user defined
parameter[1]	Values of the dynamic parameter for each HRU, which is used until another event is specified for this parameter	real	--	--

[1]The name, description, units, type, and range of the possible input parameters are defined in table 1-2. The range of each parameter value includes the value -1, which indicates to set the parameter value for an HRU to its previous value.

```
Impervious fraction updates; values derived from remote sensed data
Parameter name: hru_percent_imperv

year  month day  HRU 1      2     3      4       5      6      7
####
2009    7    1       0.0    0.0   0.01   0.08    0.02   0.20   0.0
2012   11    5       -1     0.05   -1    0.06     -1    0.21   0.0
2017    3   15       -1     0.08  0.11   0.02     -1    0.23   0.0
2030    1    1       0.01   0.12  0.15   0.0      -1    0.3    0.0
```

Figure 1–1. Example input file to specify four impervious fraction events to the dynamic_param_read module.

The `dynamic_param_read` module writes a summary file of all events within the simulation time period for all dynamic parameters. The summary file, named `dynamic_parameter.out`, is written to the user's current directory and provides the parameter name and date of the event and optionally a list of each HRU identification number for which a value is updated. The module writes the identification numbers of HRUs for which parameter values are changed from previous values when control parameter **print_debug** is specified with a value greater than or equal to `0`. As many as 20 HRU identification numbers are written per line. Figure 1-2 provides an example summary file based on the values specified in figure 1-1. The original values for the six HRUs were equal to `0.0`.

```
Parameter hru_percent_imperv updated on 2009/07/01
Values updated for HRUs:
      3      4      5      6

Parameter hru_percent_imperv updated on 2012/11/05
Values updated for HRUs:
      2      4      6

Parameter hru_percent_imperv updated on 2017/03/15
Values updated for HRUs:
      2      3      4      6

Parameter hru_percent_imperv updated on 2030/01/01
Values updated for HRUs:
      1      2      3      4      6
```

Figure 1–2. Example dynamic parameter summary file.

Dynamic Parameter Computations

This section presents methods and equations used within the `dynamic_param_read` module. See Markstrom and others (2015) for a description of computations based on these parameters. To conserve mass, any associated states of dynamic parameters are adjusted for each event of the time series. Parameters **cov_type**, **covden_sum**, **covden_win**, **transp_beg**, **transp_end**, **rad_trncf**, **sro_to_dprst_perv**, **sro_to_dprst_imperv**, and ***potet_coef*** do not require adjustments to other states. These parameters are used in various algorithms as computation coefficients or flags to determine the algorithm used to compute a hydrologic process.

Parameters **imperv_stor_max**, **soil_moist_max**, and **soil_rechr_max_frac** specify maximum water-storage capacities for impervious area, capillary reservoir, and upper zone of the capillary reservoir as the fraction of **soil_moist_max**, respectively. Any antecedent water in the associated reservoir that exceeds the specified values for these parameters is treated as inflow for the event date. This inflow is added to any rain throughfall and snowmelt prior to computations of flow on the basis of storage of the associated reservoir. If a new value for parameter **soil_moist_max** is specified less than the current water content of the capillary reservoir (variable *soil_moist*), any water in excess of parameter **soil_moist_max**, that is, inflow plus antecedent capillary storage, flows to the groundwater reservoir up to the value of parameter **soil2gw_max**, with the remainder flowing to the gravity reservoir. Parameter **soil2gw_max** is the maximum value of capillary storage excess in units of inches routed directly to the groundwater reservoir, that is, direct recharge. Any water in excess of the value of **soil_rechr_max_frac*soil_moist_max** is included in the storage of the lower zone of capillary reservoir where transpiration is computed and soil evaporation is not computed. Parameters **snow_intcp**, **srain_intcp** and **wrain_intcp** specify maximum water-storage capacities of the canopy for snow and summer and winter rain, respectively. Table 1–4 defines variables and parameters used in computations.

Table 1–4. Variables and parameters used for state variable adjustment in the Dynamic Parameter Input Module—dynamic_param_read.

[HRU, hydrologic response unit; **one**, a constant equal to 1; **nhru**, number of HRUs]

Name	Description	Dimension	Type	Unit
	Parameters input in the Parameter File(s)			
dprst_frac_open	Fraction of open surface-depression storage area within an HRU that can generate surface runoff as a function of storage volume	**nhru**	real	decimal fraction
hru_area	Area of each HRU	**nhru**	real	acres
hru_type	Type of each HRU (0=inactive; 1=land; 2=lake; 3=swale)	**nhru**	integer	none
	Variables input in the Data File			
nowday	Day of current time step	**one**	integer	day
nowmonth	Month of current time step	**one**	integer	month
nowyear	Year of current time step	**one**	integer	year
	Variables updated when **dyn_imperv_flag**=1, 2 or 3 and an impervious event date equals the current time-step date			
dprst_area_max	Area within and HRU that has surface-depression storage for each HRU	**nhru**	real	acres
dprst_area_clos_max	Area within and HRU that has closed surface-depression storage for each HRU	**nhru**	real	acres
dprst_area_open_max	Area within and HRU that has open surface-depression storage for each HRU	**nhru**	real	acres
dprst_vol_clos_max	Volume of water of closed surface-depression storage for each HRU	**nhru**	real	acre-inches
dprst_vol_open_max	Volume of water of open surface-depression storage for each HRU	**nhru**	real	acre-inches
hru_imperv	Area within an HRU that is impervious for each HRU	**nhru**	real	acres
hru_perv	Area within an HRU that is pervious for each HRU	**nhru**	real	acres
imperv_stor	Storage on impervious area for each HRU	**nhru**	real	inches
soil_moist	Storage of capillary reservoir for each HRU	**nhru**	real	inches
soil_rechr	Storage for recharge zone (upper portion) of the capillary reservoir that is available for both evaporation and transpiration for each HRU	**nhru**	real	inches

The area of an HRU (parameter **hru_area**) that is impervious (variable *hru_imperv*) is computed on the basis of the area of the HRU according to

$$hru\_imperv_{HRU} = MAX\left(\mathbf{hru\_percent\_imperv}_{HRU} \times \mathbf{hru\_area}_{HRU}, 0.999 \times \mathbf{hru\_area}_{HRU}\right). \tag{1}$$

The maximum value of **hru_percent_imperv** is 0.999 minus any surface-depression area. This limit is due to the requirement that each HRU must have a portion that is pervious to allow for cascading interflow to the capillary reservoir of downslope HRUs and to eliminate the possibility of division by zero in many computations; thus, the sum of **dprst_frac** and **hru_percent_imperv** must be less than or equal to 0.999 for each HRU. PRMS enforces this requirement by first adjusting **dprst_frac** and then the pervious area of the HRU (variable *hru_perv*) as necessary. The value of *hru_perv* for each HRU is computed according to

$$hru\_perv_{HRU} = MAX\left(\mathbf{hru\_area}_{HRU} - hru\_imperv_{HRU} - \mathbf{dprst\_frac}_{HRU} \times \mathbf{hru\_area}_{HRU}, 0.001 \times \mathbf{hru\_area}_{HRU}\right). \tag{2}$$

For events related to a change in **hru_percent_imperv** values, the depth per-unit-area of retention storage on impervious surfaces (variable *imperv_stor*) for the previous time step (i–1) is adjusted by the ratio of the previous value of **hru_percent_imperv** to the new value of each HRU. For events related to a change in **hru_percent_imperv** and (or) **dprst_frac** values, the depth per-unit-area of capillary reservoir storage (variable *soil_moist*) and the depth per-unit-area of recharge zone of capillary reservoir storage (variable *soil_rechr*) of each HRU for the previous time step is adjusted by the ratio of the previous value of *hru_perv* to the new value according to

$$imperv\_stor^{i}_{HRU} = imperv\_stor^{i-1}_{HRU} \times \frac{\boldsymbol{hru\_percent\_imperv}^{i-1}_{HRU}}{\boldsymbol{hru\_percent\_imperv}^{i}_{HRU}}, \tag{3}$$

$$soil\_moist^{i}_{HRU} = soil\_moist^{i-1}_{HRU} \times \frac{hru\_perv^{i-1}_{HRU}}{hru\_perv^{i}_{HRU}}, \text{ and} \tag{4}$$

$$soil\_rechr^{i}_{HRU} = soil\_rechr^{i-1}_{HRU} \times \frac{hru\_perv^{i-1}_{HRU}}{hru\_perv^{i}_{HRU}}. \tag{5}$$

For events related to a change in **dprst_frac** values, the maximum area for open (variable *dprst_area_open_max*) and closed (variable *dprst_area_clos_max*) surface-depression storage is recomputed on the basis of the static parameter **dprst_frac_open** and the new values for **dprst_frac** for each HRU according to

$$dprst\_area\_open\_max_{HRU} = \mathbf{dprst\_frac}_{HRU} \times \mathbf{hru\_area}_{HRU} \times \mathbf{dprst\_frac\_open}_{HRU} \text{ and} \tag{6}$$

$$dprst\_area\_clos\_max_{HRU} = \mathbf{dprst\_frac}_{HRU} \times \mathbf{hru\_area}_{HRU} - dprst\_area\_open\_max_{HRU}. \tag{7}$$

For events related to a change in **dprst_depth_avg** values, the maximum volume for open (variable *dprst_vol_open_max*) and closed (variable *dprst_vol_clos_max*) surface-depression storage is recomputed for each HRU according to

$$dprst\_vol\_open\_max_{HRU} = dprst\_area\_open\_max_{HRU} \times \mathbf{dprst\_depth\_avg}_{HRU} \text{ and} \tag{8}$$

$$dprst\_vol\_clos\_max_{HRU} = dprst\_area\_clos\_max_{HRU} \times \mathbf{dprst\_depth\_avg}_{HRU}. \tag{9}$$

The parameter **dprst_depth_avg** must have a value greater than zero or updating the value of **dprst_frac** for any HRU will not affect simulation results and vice versa.

Water-Use Input Option—Module water_use_read

The `water_use_read` module was developed to add the capability to account for constant and dynamic redistribution of water on the basis of water availability at storage locations internal and external to the model domain by using a time series of values. The module provides a method to read and apply time series of connectivity and flow rates that define water transfers between water-supply sources and water-storage destinations. There are five water-supply sources: (1) stream segment flow, (2) groundwater storage, (3) open surface-depression storage, (4) external locations, and (5) lake storage. There are eight water-storage destinations: (1) stream segments, (2) groundwater storage, (3) open surface-depression storage, (4) external locations, (5) lake storage, (6) capillary reservoir storage, (7) internal consumptive-use locations, and (8) plant canopy storage. Available water can be transferred using any source/destination combination. Multiple transfers can originate from each source, and each destination can receive water from multiple sources. This option provides the capability to evaluate historical, current, and projected changes and spatial trends in, and effects of, water use on hydrologic processes and response.

Sources of Water-Use Information

Time series of water-use information can be derived from various combinations of historical, current, and projected information. Sources could be simulation models, measured data, and water-resource management practices and scenarios, such as transfers of water for agricultural, consumptive use, and flood mitigation. Water-use data may need to be extrapolated or disaggregated for use on a daily time step. Access to a variety of water-use data and information sources may be available from Federal, State, local, international, and educational institutions.

Specification for Use of the Water-Use Input Option

Specification of the water transfer connectivity between storage locations is analogous to specifying the water conveyance features within watersheds that may be the result of human activities and natural processes. The `water_use_read` module reads time series of water-use transfer rates and applicable dates from separate files, named Water-Use Files. Because there are five source types, one to five Water-Use Files can be input for any simulation. Each entry of water-use connectivity and transfer flow rates in Water-Use Files is termed an "event," which can be specified for any date within or outside of a specified simulation time period. Only events that occur within the selected simulation time period are used; any additional events specified before or after the simulation period are ignored.

Ten new control parameters, two for each available source, activate use of the `water_use_read` module. One is a flag that specifies whether a particular transfer source is active, and the second is the name of the associated Water-Use File for that source. Additionally, two new dimensions are specified in the Parameter File, the number of external sources (**nexternal**) and the number of internal consumption locations (**nconsumed**). The following are conditions specified for each water-use transfer with the control parameters and dimensions defined in table 1–5.

- Stream segment transfers are read from file **segment_transfer_file** when **segment_transferON_OFF** is specified with the value 1 and dimension **nsegment** is specified with a value greater than 0.
- Groundwater transfers are read from file **gwr_transfer_file** when **gwr_transferON_OFF** is specified with the value 1.
- Open surface-depression storage transfers are read from file **dprst_transfer_file** when **dprst_transferON_OFF** is specified with the value 1 and control parameter **dprst_flag** is specified with the value 1.
- External transfers are read from file **external_transfer_file** when **external_transferON_OFF** is specified with the value 1 and dimension **nexternal** is specified with a value greater than 0.
- Consumptive-use destinations can be specified when dimension **nconsumed** is specified with a value greater than 0.
- Lake HRU transfers are read from file **lake_transfer_file** when **lake_transferON_OFF** is specified with the value 1, dimension **nlake** is specified with a value greater than 0, and control parameter **strmflow_module** is specified with the value `muskingum_lake` and the lake routing method is either over a broad-crested weir or time series of gate openings (parameter **lake_type** value equals `4` or `5`, respectively).

Note the source type is implicitly defined on the basis of the value of control parameters: **segment_transfer_file**, **gwr_transfer_file**, **dprst_transfer_file**, **lake_transfer_file**, and **external_transfer_file**.

Table 1–5. Input control parameters and dimensions to the Water-Use Input Module—water_use_read.

Parameter name	Description	Condition	Type	Range	Default
		Parameters input in the Control File			
dprst_transfer_file	Pathname of the time series of pre-processed flow rates for transfers from surface-depression storage	**dprst_transferON_OFF** = 1 and **dprst_flag** = 1	character	none	dprst.transfer
dprst_transferON_OFF	Flag to indicate to use time series of surface-depression transfer flow rates from the **dprst_transfer_file** (0=no; 1=yes)	surface depression transfer and **dprst_flag** = 1	integer	0 or 1	0
dprst_flag	Flag to indicate if surface-depression storage simulation is computed (0=no; 1=yes)	required	integer	0 or 1	0
external_transfer_file	Pathname of the time series of pre-processed flow rates for transfers from external sources	**external_transferON_OFF** = 1	character	none	ext.transfer
external_transferON_OFF	Flag to indicate to use external transfer flow rates from the **external_transfer_file** (0=no; 1=yes)	external transfer	integer	0 or 1	0
gwr_transfer_file	Pathname of the time series of pre-processed flow rates for transfers from groundwater reservoir storage	**gwr_transferON_OFF** = 1	character	none	gwr.transfer
gwr_transferON_OFF	Flag to indicate to use groundwater transfer flow rates from the **gwr_transfer_file** (0=no; 1=yes)	groundwater transfer	integer	0 or 1	0
lake_transfer_file	Pathname of the time series of pre-processed flow rates for transfers from lake HRUs	**lake_transferON_OFF** = 1	character	none	lake.transfer
lake_transferON_OFF	Flag to indicate to use lake HRU transfer flow rates from the **lake_transfer_file** (0=no; 1=yes)	lake water transfer	integer	0 or 1	0
segment_transfer_file	Pathname of the time series of pre-processed flow rates for transfers from stream segments	**segment_transferON_OFF** = 1	character	none	seg.transfer
segment_transferON_OFF	Flag to indicate to use stream segment transfer flow rates from the **segment_transfer_file** (0=no; 1=yes)	stream water transfer	integer	0 or 1	0
		Dimensions input in the Parameter File(s)			
nconsumed	Number of internal water-use consumption locations	consumption transfers	integer	0 to user defined	0
nexternal	Number of external source locations	external transfers	integer	0 to user defined	0
nhru	Number of hydrologic response units	required	integer	1 to user defined	1
nlake	Number of lake HRUs	lake transfers	integer	0 to user defined	0
nsegment	Number of stream segments	streamflow routing	integer	0 to user defined	0
nwateruse	Number of unique sources and destinations	water-use input	integer	0 to user defined	0
one	Dimension of scalar parameters and variables	required	integer	1	1

Specification of Water-Use Input Variables

Entries in Water-Use Files are specified as the event date, the source identification number, destination type, destination identification number, and the transfer flow-rate value. The time series specified in each Water-Use File for each source type can be input using regular and irregular intervals, as long as they are in chronological order. Each Water-Use File can specify time series of water-transfer rates that are different in terms of time period, frequency, source, and destination. Multiple connectivity and flow rates can be specified for each event date, and any number of events can be specified in a Water-Use File. The part of a time series that is included within a simulation time period is used; any additional events are ignored. Water-use transfer connectivity and flow rates can change on any time step within a simulation. Transfer rates remain constant from the event until any subsequent event for each unique pair of source and destination; thus, specified events for each transfer pair need to be of fine enough temporal resolution to represent the desired water-use changes as the code does not interpolate between events. The users must specify a rate of zero to end a transfer. The input variables specified in Water-Use File for each water-use event are defined in. These variables must be input in the order defined in the table.

The time-series transfer flow-rate variables computed by the `water_use_read` module are defined in table 1–7. Each variable is computed on the basis of the total transfers from each source type and destination for each time step. These transfer flow rates remain constant until the next event, at which time the variables associated with the connectivity are updated. Water withdrawals are positive values and return flows are negative values.

Figure 1–3 provides an example Water-Use File (control parameter **segment_transfer_file**) to specify stream segment transfers. This example specifies 3 water-use events originating from stream segments 3, 53, and 12. The first two events (July 1, 2009) transfer water to the open surface-depression storage of HRUs 132 and 22, respectively, and the third event (November 5, 2011) transfers water to stream segment 6. Any number of spaces can be used between values. Lines preceding the line that begins with four “#” characters are ignored. However, it is encouraged that users provide information that describes the data source of the events specified in the file. The units of the “value” field in the Water-Use Files are cubic feet per second.

Table 1–6. Variables for a water-use event as read by the Water-Use Input Module—water_use_read.

[HRU, hydrologic response unit; cfs, cubic feet per second]

Variable name	Description	Unit	Type	Range
year	Year of the water-use event	year	integer	user defined
month	Month of the water-use event	month	integer	user defined
day	Day of the water-use event	day	integer	user defined
src_id	Identification number of the source type	none	integer	1 to dimension of source type
dest_type	Destination type to which the transfer rates are applied for an event (1=stream segment; 2=groundwater reservoir of an HRU; 3=open surface-depression storage of an HRU; 4=external location; 5=lake HRU; 6=capillary reservoir storage of an HRU; 7=consumptive-use location; 8=plant canopy of an HRU)	none	integer	1 to 8
dest_id	Identification number of the destination, which can be a stream segment, HRU, external location, or consumptive-use location identification number depending on the value of *dest_type*	none	integer	1 to dimension of destination type
transfer_rate	Value of the transfer flow rate, which is used until another value is specified with the same *src_id*, *dest_type*, and *dest_id* in the transfer source input file	cfs	real	user defined

Table 1–7. Variables computed by the Water-Use Input Module—water_use_read.

[HRU, hydrologic response unit; **one**, a constant equal to 1; **nhru**, number of HRUs; **nsegment**, number of stream segments; **nexternal**, number of external sources plus destinations; cfs, cubic feet per second]

Variable name	Description	Condition	Input File or Output	Dimension	Unit	Type
		Stream segment water use				
segment_gain	Transfer gain to each stream segment for sources other than the stream network	*dest_type* = 1	output	**nsegment**	cfs	real
seg_lateral_inflow	Lateral inflow to each stream segment from which any segment transfers are subtracted and segment gains are added	*dest_type* = 1 or **segment_transferON_OFF** = 1	output	**nsegment**	cfs	real
segment_transfer	Transfer flow rate from each stream segment	**segment_transferON_OFF** = 1	segment_transfer_file	**nsegment**	cfs	real
total_segment_gain	Transfer gains to all stream segments	*dest_type* = 1	output	**one**	cfs	real
total_segment_transfer	Transfer flow rates from all segments	**segment_transferON_OFF** = 1	output	**one**	cfs	real
		Groundwater water use				
gwr_gain	Transfer gain to groundwater reservoir of each HRU	*dest_type* = 2	output	**nhru**	cfs	real
gwr_transfer	Transfer flow rate from the groundwater reservoir of each HRU	**gwr_transferON_OFF** = 1	gwr_transfer_file	**nhru**	cfs	real
gwres_stor	Storage in each groundwater reservoir	*dest_type* = 2	output	**ngw**	inches	double
total_gwr_gain	Transfer gains to all groundwater reservoirs	*dest_type* = 2	output	**one**	cfs	real
total_gwr_transfer	Transfer flow rates from all groundwater reservoirs	**gwr_transferON_OFF** = 1	output	**one**	cfs	real
		Surface-depression storage water use				
dprst_gain	Transfer gain to surface-depression storage for each HRU	*dest_type* = 3	output	**nhru**	cfs	real
dprst_transfer	Transfer flow rate from surface-depression storage for each HRU	**dprst_transferON_OFF** = 1	dprst_transfer_file	**nhru**	cfs	real
total_dprst_gain	Transfer gains to all surface-depression storage	*dest_type* = 3	output	**one**	cfs	real
total_dprst_transfer	Transfer flow rates from all surface-depression storage	**dprst_transferON_OFF** = 1	output	**one**	cfs	real
		External location water use				
external_gain	Transfer gain to each external location of the model domain	*dest_type*e = 4	output	**nexternal**	cfs	real
external_transfer	Transfer flow rate from each external source of the model domain	**external_transferON_OFF** = 1	external_transfer_file	**nexternal**	cfs	real
total_external_gain	Transfer gains to all external locations of the model domain	*dest_type* = 4	output	**one**	cfs	real
total_external_transfer	Transfer flow rates from all external sources of the model domain	**external_transferON_OFF** = 1	output	**one**	cfs	real

Table 1–7. Variables computed by the Water-Use Input Module—water_use_read.—Continued

[HRU, hydrologic response unit; **one**, a constant equal to 1; **nhru**, number of HRUs; **nsegment**, number of stream segments; **nexternal**, number of external sources plus destinations; cfs, cubic feet per second]

Variable name	Description	Condition	Input File or Output	Dimension	Unit	Type
		Lake water use				
lake_gain	Transfer gain to each lake HRU	*dest_type* = 5	output	**nhru**	cfs	real
lake_transfer	Transfer flow rate from each lake HRU	**lake_transferON_OFF** = 1	lake_transfer_file	**nhru**	cfs	real
total_lake_gain	Transfer gains to all lake HRUs	*dest_type* = 5	output	**one**	cfs	real
total_lake_transfer	Transfer flow rates from all lake HRUs	**lake_transferON_OFF** = 1	output	**one**	cfs	real
		Soilzone water use				
soilzone_gain	Transfer gain to the capillary reservoir within the soil zone for each HRU	*dest_type* = 6	output	**nhru**	cfs	real
total_soilzone_gain	Transfer gains to all capillary reservoirs	*dest_type* = 6	output	**one**	cfs	real
		Consumption water use				
consumed_gain	Transfer gain to each water-use consumption destination within the model domain	*dest_type* = 7	output	**nconsumed**	cfs	real
total_consumed_gain	Transfer gains to all water-use consumption destinations	*dest_type* = 7	output	**one**	cfs	real
		Canopy water use				
canopy_gain	Transfer gain to the plant canopy of each HRU	*dest_type* = 8	output	**nhru**	cfs	real
total_canopy_gain	Transfer gains to all plant canopy reservoirs	*dest_type* = 8	output	**one**	cfs	real

```
Streamflow transfer values from the department of natural resources
year  month day   src_id   dest_type dest_id   value
####
2009   7     1       3          3        132      10.0
2009   7     1      53          3        22       50.0
2011   11    5      12          1        6       113.0
```

Figure 1–3. Example input file to specify three water-use events to the water_use_read module.

The `water_use_read` module writes a summary file of all events specified in Water-Use Files that are used within the simulation time period. The summary file, named `water_use.out`, is written to the user's current directory. It consists of four lines that lists the date, connectivity (source name and identification number and destination name and identification number), and flow rate for each event. Figure 1–4 provides an example summary output file based on the values specified in figure 1–3.

```
Water Use Summary File

Simulation Start Date: 2005/10/01   End Date: 2020/09/30

Event date: 2009/07/01
Source: stream segment:     3
Destination: open surface-depression storage, HRU:   132
Transfer flow rate:   10.00

Event date: 2009/07/01
Source: stream segment     53
Destination: open surface-depression storage, HRU:    22
Transfer flow rate:   50.00

Event date: 2011/11/05
Source: stream segment:     12
Destination: stream segment:     6
Transfer flow rate:   113.00
```

Figure 1–4. Example output file for the water_use_read module.

Water-Use Computations

This section presents the methods and the equations used within the `water_use_read` module. The module keeps track of daily and total flows from each source, applies the flow to the specified storage of the destination, and adjusts dependent model states related to the transfer. Transferred water is added to any existing water storage of the destination at the start of the time step. The amount of transferred water is limited based on the antecedent storage in the source. If the transferred water exceeds the storage capacity of the destination, the storage is adjusted on the time step using existing algorithms.

Output variables are computed to summarize transfers from each source and inflows to each destination. Many computations in PRMS use variables in units of inches as a depth per-unit-area for each day of the simulation. The variable *transfer_rate* used in the water-use computation equations is used as a generic name for all transfers to a destination and is dimensioned by the value of **nwateruse**. Equations 13, 15, 17, 18, 20, 21, 22, 24, 26, 28, 30, and 33 show a summation of transfer rates for 1 to **nwateruse**; however, only those transfers related to the source or destination are summed. Thus, for each transfer type there could be 1 to **nwateruse** transfer rates or none. The conversion from inch-acres per day to cubic feet per second (cfs) is computed according to

$$cfs\_conv = 0.04201389 = 43,560\frac{feet^2}{acre}\times\frac{1\,foot}{12\,inches}\times\frac{1\,day}{86,400\,seconds}\,. \qquad (10)$$

The transfer from a groundwater reservoir in units of cfs for each time step and allowing for multiple transfers is computed according to

$$gwr\_transfer_{HRU} = gwr\_transfer_{HRU} + \sum_{i=1}^{\mathbf{nwateruse}} transfer\_rate_i \ . \tag{11}$$

Storage in the groundwater reservoir is computed as a depth per-unit-area in units of inches for each time step, using the variable *gwres_stor* and the sum of all water-use transfers from groundwater reservoirs, g*wr_transfer*, according to

$$gwres\_stor_{HRU} = gwres\_stor_{HRU} - \left(gw\_transfer_{HRU} \Big/ \left(cfs\_conv \times \mathbf{hru\_area}_{HRU} \right) \right). \tag{12}$$

If accounting for transfers from available water in any groundwater reservoir results in negative storage, the simulation stops and an error message is produced. In that case, the transfer(s) from the groundwater reservoir must be reduced and (or) the amount of storage must be increased by adjusting parameters related to inflow to and outflow from the groundwater reservoir for a subsequent simulation. See Markstrom and others (2015) for descriptions of the parameters and flow variables related to groundwater reservoirs.

The transfer from open surface-depression storage, in units of cfs, for each time step and allowing for multiple transfers is computed according to

$$dprst\_transfer_{HRU} = dprst\_transfer_{HRU} + \sum_{i=1}^{\mathbf{nwateruse}} transfer\_rate_i \ . \tag{13}$$

Storage in open surface-depression storage is computed as a volume in units of inch-acres for each time step, using the variable *dprst_vol_open* and the sum of all water-use transfers from the storage, *dprst_transfer*, according to

$$dprst\_vol\_open_{HRU} = dprst\_vol\_open_{HRU} - \left(dprst\_transfer_{HRU} \Big/ cfs\_conv \right). \tag{14}$$

If accounting for transfers from *dprst_vol_open* for any HRU results in negative storage, the simulation stops and an error message is produced. In that case, the transfers from surface-depression storage for that HRU must be reduced and (or) the amount of open surface-depression storage in the HRU must be increased by adjusting parameters related to area, inflow to, and (or) outflow from open surface-depression storage for subsequent simulations. See Markstrom and others (2015) and the Surface-Depression Storage Simulation Capability section of this manual for descriptions of the parameters and flow variables related to open surface-depression storage.

The transfer from a stream segment in units of cfs for each time step and allowing for multiple transfers is computed according to

$$segment\_transfer_{SEG} = segment\_transfer_{SEG} + \sum_{i=1}^{\mathbf{nwateruse}} transfer\_rate_i \ . \tag{15}$$

Transferred water to a stream segment is treated as lateral inflow (variable *seg_lateral_inflow*) in units of cfs for each time step. The sum of all water-use transfers from the stream segment, *segment_transfer*, is subtracted from *seg_lateral_inflow* according to

$$seg\_lateral\_inflow_{SEG} = seg\_lateral\_inflow_{SEG} - segment\_transfer_{SEG} \ . \tag{16}$$

If accounting for transfers for any stream segment results in negative flow on a time step, an error message is produced and the simulation terminates. In that case, the transfers for that stream segment may need to be reduced by adjusting parameters related to inflow to and outflow from the stream segment if the reduction to the available water storage is inappropriate. See Markstrom and others (2015) for descriptions of the parameters and flow variables related to stream segment computations in the `muskingum` module and the Stream and Lake Flow-Routing Simulation Capability—Module `muskingum_lake` section in this manual.

Transfer flow rates in units of cfs for each time step from external sources are assumed to be from an infinite water-supply source and allow for multiple transfers from each source. The total transfer from each external source is computed according to

$$external\_transfer_{EXT} = external\_transfer_{EXT} + \sum_{i=1}^{\mathbf{nwateruse}} transfer\_rate_i \; . \tag{17}$$

The transfer from storage for a lake HRU, in units of cfs, for each time step and allowing for multiple transfers is computed according to

$$lake\_transfer_{HRU} = lake\_transfer_{HRU} + \sum_{i=1}^{\mathbf{nwateruse}} transfer\_rate_i \; . \tag{18}$$

Storage in each lake HRU is computed as a volume in units of acre-feet for each time step using the variable *lake_vol* and the sum of all water-use transfers from lake HRUs using the variable *lake_transfer*, according to

$$lake\_vol_{HRU} = lake\_vol_{HRU} - \left({lake\_transfer_{HRU}} \Big/ {cfs\_conv} \right) . \tag{19}$$

If accounting for transfers from *lake_vol* for any lake HRU results in negative storage, the simulation stops and an error message is produced. In that case, the transfer(s) from the lake HRU must be reduced and (or) the amount of storage must be increased by adjusting parameters related to inflow to and outflow from the lake HRU. Storage in lake HRUs is available when either the `strmflow_lake` or `muskingum_lake` module is active and the value of parameter **lake_type** has the value `4` or `5`. See Markstrom and others (2015) for descriptions of the `strmflow_lake` module and the Stream and Lake Flow-Routing Simulation Capability—Module `muskingum_lake` section in this appendix for the parameters and flow variables related to lake HRUs.

Transfers from source locations to destination locations are not limited by the storage capacity of the destination and are treated as a gain to the destination in the same manner as any other inflow to the destination storage. If the gain from transfers exceeds the storage capacity of the destination, the computations for hydrologic processes related to the destination will conserve mass by routing any excess storage. Any of the eight destinations can receive water from any of the five source locations. Water transferred to external (eq. 20) and internal consumptive-use (eq. 21) locations and stream segments (eq. 22) from any source and time step are computed according to

$$external\_gain_{EXT} = external\_gain_{EXT} + \sum_{i=1}^{\mathbf{nwateruse}} transfer\_rate_i \; , \tag{20}$$

$$comsumed\_gain_{CON} = consumed\_gain_{CON} + \sum_{i=1}^{\mathbf{nwateruse}} transfer\_rate_i \; , \text{ and} \tag{21}$$

$$segment\_gain_{SEG} = segment\_gain_{SEG} + \sum_{i=1}^{\mathbf{nwateruse}} transfer\_rate_i \; . \tag{22}$$

Transferred water to a stream segment is treated as lateral inflow in units of cfs for each time step. The sum of all water-use transfers to the stream segment, *segment_gain*, is added to *seg_lateral_inflow* according to

$$seg\_lateral\_inflow_{SEG} = seg\_lateral\_inflow_{SEG} + segment\_gain_{SEG} \; . \tag{23}$$

Water transferred to groundwater storage of any HRU and time step are computed according to

$$gwr\_gain_{HRU} = gwr\_gain_{HRU} + \sum_{i=1}^{\mathbf{nwateruse}} transfer\_rate_i \; \text{ and} \tag{24}$$

$$gwres\_stor_{HRU} = gwres\_stor_{HRU} + \left({gw\_gain_{HRU}} \Big/ \left(cfs\_conv \times \mathbf{hru\_area}_{HRU} \right) \right) . \tag{25}$$

Water transferred to open surface-depression storage of any HRU and time step are computed according to

$$dprst\_gain_{HRU} = dprst\_gain_{HRU} + \sum_{i=1}^{\mathbf{nwateruse}} transfers_i \text{ and} \tag{26}$$

$$dprst\_vol\_open_{HRU} = dprst\_vol\_open_{HRU} + \left({dprst\_gain_{HRU}} \big/ {cfs\_conv} \right). \tag{27}$$

Water transferred to lake HRUs for each time step are computed according to

$$lake\_gain_{HRU} = lake\_gain_{HRU} + \sum_{i=1}^{\mathbf{nwateruse}} transfers_i \text{ and} \tag{28}$$

$$lake\_vol_{HRU} = lake\_vol_{HRU} + \left({lake\_gain_{HRU}} \big/ {cfs\_conv} \right). \tag{29}$$

Water transferred to capillary reservoir storage of the soil zone for the pervious area of any HRU and time step are computed according to

$$soilzone\_gain_{HRU} = soilzone\_gain_{HRU} + \sum_{i=1}^{\mathbf{nwateruse}} transfer\_rate_i \text{ ,} \tag{30}$$

$$soil\_most_{HRU} = soil\_moist_{HRU} + \left({soilzone\_gain_{HRU}} \big/ {\left(cfs\_conv \times \mathbf{hru\_perv}_{HRU}\right)} \right) \text{, and} \tag{31}$$

$$soil\_rechr_{HRU} = soil\_rechr_{HRU} + \left({soilzone\_gain_{HRU}} \big/ {\left(cfs\_conv \times \mathbf{hru\_perv}_{HRU}\right)} \right). \tag{32}$$

Water transferred to plant canopy storage of any HRU and time step are computed according to

$$canopy\_gain_{HRU} = canopy\_gain_{HRU} + \sum_{i=1}^{\mathbf{nwateruse}} transfer\_rate_i \text{ and} \tag{33}$$

$$intcp\_stor_{HRU} = intcp\_stor_{HRU} + \left({canopy\_gain_{HRU}} \big/ {cfs\_conv} \right). \tag{34}$$

HRU Summary Output Option—Module nhru_summary

The `nhru_summary` module was developed to add the capability to write files of daily, monthly, and (or) mean monthly values of user-selected variables in a comma-separated values (CSV) format. These files are called Nhru Summary Files and each has the number of values per line equal to the number of HRUs. The CSV format allows simulation results to be directly input to other software, such as statistical, graphical, and simulation models. Additionally, these files could be used to generate input information required for other simulation codes, that is, a method to loosely couple PRMS with other simulation codes.

Any number of variables that are dimensioned by the value of **nhru** can be output. A separate file is generated for each selected variable. The module provides for specification of a warmup time period (parameter **prms_warmup** in the Parameter File) to allow the simulation results to reach equilibrium between applied climatic conditions and dynamic surface hydrologic processes prior to writing to NHRU Summary Files. Several new control parameters, input in the Control File, have been added that specify whether to output Nhru Summary Files, the number and name of output variables, and the base file name for each file (table 1–8). Each output file has the name of the variable appended to the base file name.

Table 1–8. Input parameters to the NHRU Summary Module—nhru_summary.

Parameter name	Description	Number	Type	Range	Default
		Parameter input in the Control File			
nhruOutBaseFileName[1]	String to define the prefix for each Nhru Summary Results File	1	character	user defined	nhruout_path
nhruOutON_OFF	Switch to specify whether or not Nhru Summary Results Files are generated (0=no; 1=yes)	1	integer	0 or 1	0
nhruOutVar_names	List of variable names for which output is written to nhru summary Comma Separated Values (CSV) output files(s). Each variable is written to a separate file with the prefix of each file equal to the value of **nhruOutBaseFileName**	**nhruOutVars**	character	user defined	none
nhruOutVars	Number of variables to include in Nhru Summary Results File(s)	1	integer	user defined	0
nhruOut_freq	Output frequency and type (1=daily; 2=monthly; 3=both; 4=mean monthly)	1	integer	0 to 4	1
prms_warmup	Number of years to simulate before writing Nhru Summary Results Files	1	integer	0 to user defined	1

[1]Pathnames can be specified using a maximum of 132 characters.

Figure 1–5 shows a portion of a Control File to specify the parameters required to produce three Nhru Summary Files. One file is created for each output type: potential ET, actual ET, and recharge with the filenames `./modeltest/prmsIV_potet.csv`, `./modeltest/prmsIV_hru_actet.csv`, and `./modeltest/prmsIV_recharge.csv`, respectively.

```
####
nhruOutBaseFileName
1
4
./modeltest/prmsIV_
####
nhruOutON_OFF
1
1
1
####
nhruOutVars_names
3
4
potet
hru_actet
recharge
####
nhruOutVars
1
1
3
```

Figure 1–5. Example portion of a Control File used with the nhru_summary module.

Basin Variables Summary Output Option—Module prms_summary

The `prms_summary` module was developed to add the capability to write time-series CSV format files, named PRMS Summary Files, of daily values of basin-area average variables and optionally pairs of simulated and measured streamflow. The CSV format allows simulation results to be directly input to other software, such as statistical, graphical, and simulation models. Additionally, these summary files could be used to generate input information required for other simulation codes. Three new control parameters, specified in the Control File, and a new dimension and two new parameters, specified in the Parameter File, are used by the `prms_summary` module (table 1–9). These parameters specify whether to output the PRMS Summary File (control parameter **csvON_OFF**), the output summary file name (control parameter **csv_output_file**), the warmup time period (control parameter **prms_warmup**), the number of simulated and measured streamflow pairs (dimension **npoigages**), identification string for each measured streamflow gage (**poi_gage_id**), and segment identification number (**poi_gage_segment**) associated with each gage. The variables written to the Basin Variables Summary File are shown in table 1–10.

Table 1–9. Input parameters to the Basin Variables Summary Module—prms_summary.

Parameter name	Description	Number	Type	Range	Default
		Parameter input in the Control File			
csvON_OFF	Switch to specify whether or not common-separated values (CSV) Basin Variables Summary File is generated (0=no; 1=yes)	1	integer	0 or 1	0
csv_output_file	Pathname of CSV output file for the set of basin-area weighted variables	1	character	user defined	prms_summary.csv
prms_warmup	Number of years to simulate before writing Basin Variables Summary File	1	integer	0 to user defined	1
		Dimension and Parameters input in the Parameter File			
npoigages	Number of simulated and measured streamflow pairs to include in the Basin Variables Summary File	1	integer	user defined	0
poi_gage_id[1]	USGS stream gage identification string for this point of interest (POI)	**npoigages**	character	user defined	0
poi_gage_segment	Segment index for gage POI	**npoigages**	integer	1 to n**segment**	1

[1]Gage identification values can have a maximum of 16 characters.

Table 1–10. Variables written to the Basin Variables CSV File.

[**one**: a constant equal to 1; **nsegment**: number of stream segment; **nob**s: number of measured runoff stations specified in Data File; inches: inches per unit area; cfs: cubic feet per second; ET: evapotranspiration; GWRs: groundwater reservoirs]

Variable name	Description	Dimension	Unit	Type
date	Date of timestep	**one**	year-month-day	character
basin_potet	Basin area-weighted average potential ET	**one**	inches/day	double
basin_actet	Basin area-weighted average actual ET	**one**	inches/day	double
basin_dprst_evap	Basin area-weighted average evaporation from surface-depression storage	**one**	inches/day	double
basin_imperv_evap	Basin area-weighted average evaporation from impervious area	**one**	inches/day	double
basin_intcp_evap	Basin area-weighted evaporation from the canopy	**one**	inches/day	double
basin_lakeevap	Basin area-weighted average lake evaporation	**one**	inches/day	double
basin_perv_et	Basin area-weighted average ET from capillary reservoirs	**one**	inches/day	double
basin_snowevap	Basin area-weighted average evaporation and sublimation from snowpack	**one**	inches/day	double

Table 1–10. Variables written to the Basin Variables CSV File.—Continued

[**one**: a constant equal to 1; **nsegment**: number of stream segment; **nob**s: number of measured runoff stations specified in Data File; inches: inches per unit area; cfs: cubic feet per second; ET: evapotranspiration; GWRs: groundwater reservoirs]

Variable name	Description	Dimension	Unit	Type
date	Date of timestep	**one**	year-month-day	character
basin_swrad	Basin area-weighted average shortwave radiation	**one**	Langleys	double
basin_ppt	Basin area-weighted average precipitation	**one**	inches/day	double
basin_pk_precip	Basin area-weighted average precipitation added to snowpack	**one**	inches/day	double
basin_tmax	Basin area-weighted average maximum air temperature	**one**	degrees	double
basin_tmin	Basin area-weighted average minimum air temperature	**one**	degrees	double
basin_snowcov	Basin area-weighted average snow-covered area	**one**	decimal fraction	double
basin_total_storage	Basin area-weighted average storage in all water storage reservoirs	**one**	inches	double
basin_surface_storage	Basin area-weighted average storage in all surface water storage reservoirs	**one**	inches	double
basin_dprst_volcl	Basin area-weighted average storage volume in closed surface depressions	**one**	inches	double
basin_dprst_volop	Basin area-weighted average storage volume in open surface depressions	**one**	inches	double
basin_gwstor	Basin area-weighted average of storage in GWRs	**one**	inches	double
basin_imperv_stor	Basin area-weighted average storage on impervious area	**one**	inches	double
basin_intcp_stor	Basin area-weighted average interception storage	**one**	inches	double
basin_lake_stor	Basin volume-weighted average storage for all lakes using broad-crested weir or gate opening routing	**one**	inches	double
basin_pweqv	Basin area-weighted average snowpack water equivalent	**one**	inches	double
basin_soil_moist	Basin area-weighted average capillary reservoir storage	**one**	inches	double
basin_ssstor	Basin weighted average gravity and preferential-flow reservoir storage	**one**	inches	double
basin_pref_stor	Basin area-weighted average storage in preferential-flow reservoirs	**one**	inches	double
basin_slstor	Basin area-weighted average storage of gravity reservoirs	**one**	inches	double
basin_soil_rechr	Basin area-weighted average storage for recharge zone; upper portion of capillary reservoir where both evaporation and transpiration occurs	**one**	inches	double
basin_capwaterin	Basin area-weighted average infiltration, cascading interflow and Dunnian flow added to capillary reservoir storage	**one**	inches/day	double
basin_dprst_seep	Basin area-weighted average seepage from surface-depression storage	**one**	inches/day	double
basin_gwin	Basin area-weighted average of inflow to groundwater reservoirs	**one**	inches/day	double
basin_pref_flow_in	Basin area-weighted average infiltration to preferential-flow reservoir storage	**one**	inches/day	double
basin_recharge	Basin area-weighted average recharge to GWRs	**one**	inches/day	double
basin_snowmelt	Basin area-weighted average snowmelt	**one**	inches/day	double
basin_soil_to_gw	Basin average excess flow to capillary reservoirs that drains to GWRs	**one**	inches/day	double
basin_sz2gw	Basin area-weighted average drainage from gravity reservoirs to GWRs	**one**	inches/day	double

Table 1–10. Variables written to the Basin Variables CSV File.—Continued

[**one**: a constant equal to 1; **nsegment**: number of stream segment; **nobs**: number of measured runoff stations specified in Data File; inches: inches per unit area; cfs: cubic feet per second; ET: evapotranspiration; GWRs: groundwater reservoirs]

Variable name	Description	Dimension	Unit	Type
date	Date of timestep	**one**	year-month-day	character
basin_gwsink	Basin area-weighted average of GWR outflow to the groundwater sink	**one**	inches/day	double
basin_prefflow	Basin area-weighted average interflow from preferential-flow reservoirs to the stream network	**one**	inches/day	double
basin_slowflow	Basin area-weighted average interflow from gravity reservoirs to the stream network	**one**	inches/day	double
basin_hortonian	Basin area-weighted average Hortonian runoff	**one**	inches/day	double
basin_dunnian	Basin area-weighted average Dunnian surface runoff that flows to the stream network	**one**	inches/day	double
basin_stflow_in	Basin area-weighted average lateral flow entering the stream network	**one**	inches/day	double
basin_stflow_out	Basin area-weighted average streamflow leaving through the stream network	**one**	inches/day	double
basin_gwflow	Basin area-weighted average of groundwater flow to the stream network	**one**	inches/day	double
basin_dnflow	Basin area-weighted average of cascading groundwater flow	**one**	inches/day	double
basin_gwstor_minarea_wb	Basin area-weighted average storage added to each GWR when storage is less than **gwstor_min**	**one**	inches	double
basin_cfs	Streamflow leaving the basin through the stream network	**one**	cfs	double
basin_gwflow_cfs	Basin area-weighted average of groundwater flow to the stream network	**one**	cfs	double
basin_sroff_cfs	Surface runoff leaving the basin through the stream network	**one**	cfs	double
basin_ssflow_cfs	Interflow leaving the basin through the stream network	**one**	cfs	double
runoff_cfs	Streamflow of first streamflow measurement station in Data File	**nobs**	cfs	real
seg_outflow	Streamflow of each segment specified by parameter **poi_gage_segment**	**nsegment**	cfs	real

Figure 1–6 shows a portion of a Control File to specify the parameters required to use the `prms_summary` module.

```
####
csv_output_file
1
4
./output/basin_summary.csv
####
csvON_OFF
1
1
1
```

Figure 1–6. Example portion of a Control File used with the prms_summary module.

Stream and Lake Flow-Routing Simulation Capability—Module muskingum_lake

The `muskingum_lake` module was developed as an integration of the `muskingum` and `strmflow_lake` modules as documented in Markstrom and others (2015). Previously, for applications with on-channel lakes using the `strmflow_lake` module, streamflow into lakes was assumed to be based on continuity, that is, flow in each stream segment was routed as inflow equals outflow. This new module adds the Muskingum streamflow-routing method (Linsley and others, 1982) and the capability to set outflow from a lake equal to measured values to explicitly account for lake management operations. Simulation of lake hydrologic processes is not intended for complex operations and rule-based, decision support, but provides rudimentary routing methods requiring minimal input and computation time. Six options are available to route water through a lake: (1) flow through; (2) linear; (3) modified Puls; (4) broad-crested weir; (5) gate-opening rating table; and (6) replacement flow that sets the variable *lake_outflow* to measured streamflow. The routing option for each lake is specified on the basis of parameter **lake_type**. Table 1–11 defines parameters input to the `muskingum_lake` module.

The `muskingum_lake` module is selected by specifying `muskingum_lake` for the control parameter **strmflow_module**. Computations are identical as described for the `muskingum` and `strmflow_lake` modules except that the outflow from a lake (variable *lake_outcfs*) is added to the inflow (variable *seg_inflow*) of the downstream segment. Additionally, the outflow for the segment (variable *seg_outflow*) associated with the lake is set to the value of the variable *lake_outcfs*. A new option was added to set the variable *lake_outcfs* to measured values specified in the Data File for a selected streamgage. This allows for explicit accounting for reservoir operations; however, use of this option does not maintain a complete water balance because the state of the lake is computed but not included in the water balance. The option to have a second outflow from lakes that was included in the `strmflow_lake` module has been removed as has the `strmflow_lake` module. Table 1–12 defines variables used in the `muskingum_lake` module.

Typically, when streamflow routing is active, each HRU is associated with one stream segment and each segment is associated with the pair of adjacent left- and right-bank HRUs. However, any number of HRUs can be associated with each stream segment. Computed states and fluxes depend on the type of flow routing. For routing to lake HRUs, lateral flow from associated HRUs and streamflow from associated segments are added to an internal lake stream segment, which is used to accumulate inflow that is added to lake storage. Lateral flows are surface runoff, interflow, and groundwater discharge. An alternative method to route lateral flows to lakes is use of the cascading-flow option (`cascade` module, Markstrom and others, 2015). This cascading-flow option allows HRUs to be associated with any number of downslope HRUs and stream segments. For the cascading-flow option, lateral flows are routed directly to lake HRUs, with or without an internal stream segment. For both the typical and the cascading-flow options, simulated lake inflows include precipitation, as well as lateral flow and streamflow. Ice cover and snowpack accumulation and melt on lake surfaces are not simulated; all precipitation is added to lake storage.

Evaporation, precipitation, and outflow from and upstream inflow and lateral inflow to lakes are computed for each option. Lake water evaporates from lakes at the potential evapotranspiration rate while allowing for a monthly adjustment factor. Lake seepage, groundwater discharge, elevation, and volume of lakes are computed for **lake_type** options 4 and 5. The specification of replacement flows, option 6, for lake outflow could be used to account for the lake storage regulation.

Table 1–11. Input parameters to the Muskingum and Lake Routing Module—muskingum_lake.

[HRU, hydrologic response unit; GWR, groundwater reservoir; **one**, a constant equal to 1; **nsegment**, number of stream segments; **nmonths**, a constant equal to 12; **nhru**, number of HRUs; **nobs**, number of streamflow gaging stations; **nlake**, number of lake HRUs; **nlakeelev**, maximum number of lake elevations in any rating table; **nratetbl**, number of rating tables for lakes; **ncascade**, total number of connections among HRUs and stream segments; **mxnsos**, maximum number of storage/outflow table values for number of lake HRUs using Puls routing; **nstage**, **nstage2**, **nstage3**, and **nstage4**, maximum number of lake elevations values (rows) for lake rating tables 1, 2, 3, and 4, respectively; ngate, ngate2, ngate3, and ngate4 maximum number of reservoir gate-opening values (columns) for lake rating tables 1, 2, 3, and 4, respectively; cfs, cubic feet per second]

Parameter name	Description	Condition	Dimension	Unit	Type	Range	Default
		Parameter input in the Control File					
strmflow_module	Module name for streamflow routing simulation method	required	**one**	none	character	strmflow, strmflow_in_out, muskingum_lake	strmflow
		Parameters input in the Parameter File(s)					
elev_outflow	Elevation of the main outflow point for each lake using broad-crested weir routing	broad-crested weir routing	**nlake**	feet	real	-300.0 to 10,000.0	0.0
elevlake_init	Initial lake surface elevation for each lake using broad-crested weir routing or gate opening routing	broad-crested weir or gate opening routing	**nlake**	feet	real	-300.0 to 10,000.0	1.0
gw_seep_coef	Linear coefficient in equation to compute lakebed seepage to the GWR and groundwater discharge to each lake using broad-crested weir routing or gate opening routing	broad-crested weir or gate opening routing	**nlake**	fraction/day	real	0.001 to 0.05	0.015
hru_down_id[1]	Index number of the downslope HRU to which the upslope HRU contributes flow	**cascade_flag** = 1 and **ncascade** > 0	**ncascade**	none	integer	0 to **nhru**	0
hru_pct_up	Fraction of HRU area used to compute flow contributed to a down slope HRU or stream segment for cascade area	**cascade_flag** = 1 and **ncascade** > 0	**ncascade**	decimal fraction	real	0 or 1	0
hru_segment	Segment index to which an HRU contributes lateral flows (surface runoff, interflow, and groundwater discharge)	required	**nhru**	none	integer	0 to **nsegment**	0
hru_strmseg_down_id[1]	Index number of the stream segment to which the cascade area contributes flow	**cascade_flag** = 1 and **ncascade** > 0	**ncascade**	none	integer	0 to **nsegment**	0
hru_up_id	Index of HRU containing cascade area; used when control parameter **cascade_flag** = 1 and dimension **ncascade** > 0	**cascade_flag** = 1 and **ncascade** > 0	**ncascade**	none	integer	0 to **nhru**	0

Table 1–11. Input parameters to the Muskingum and Lake Routing Module—muskingum_lake.—Continued

[HRU, hydrologic response unit; GWR, groundwater reservoir; **one**, a constant equal to 1; **nsegment**, number of stream segments; **nmonths**, a constant equal to 12; **nhru**, number of HRUs; **nobs**, number of streamflow gaging stations; **nlake**, number of lake HRUs; **nlakeelev**, maximum number of lake elevations in any rating table; **nratetbl**, number of rating tables for lakes; **ncascade**, total number of connections among HRUs and stream segments; **mxnsos**, maximum number of storage/outflow table values for number of lake HRUs using Puls routing; **nstage**, **nstage2**, **nstage3**, and **nstage4**, maximum number of lake elevations values (rows) for lake rating tables 1, 2, 3, and 4, respectively; ngate, ngate2, ngate3, and ngate4 maximum number of reservoir gate-opening values (columns) for lake rating tables 1, 2, 3, and 4, respectively; cfs, cubic feet per second]

Parameter name	Description	Condition	Dimension	Unit	Type	Range	Default
K_coef	Travel time of flood wave from one segment to the next downstream segment, called the Muskingum storage coefficient; enter 0.0 for reservoirs, diversions, and segment(s) flowing out of the basin	required	**nsegment**	hours	real	1.0 to 24.0	1.0
lake_coef	Coefficient in equation to route storage to streamflow for each lake using linear routing	linear routing	**nlake**	fraction/day	real	0.0001 to 1.0	0.1
lake_din1	Initial inflow to each lake using Puls or linear storage routing	Puls or linear routing	**nlake**	cfs	real	0.0 to 1.0E7	0.1
lake_evap_adj	Monthly (January to December) adjustment factor for potential ET for each lake	required	**nhru**	decimal fraction	real	0.5 to 1.0	1.0
lake_hru	Index of HRU for each lake HRU	required	**nlake**	none	integer	0 to nhru	0
lake_hru_id	Identification number of the lake associated with an HRU; more than one HRU can be associated with each lake	required	**nhru**	none	integer	0 to nlake	0
lake_init	Initial storage in each lake using Puls or linear storage routing	Puls or linear routing	**nlake**	cfs-days	real	0.0 to 1.0E7	0.0
lake_qro	Initial daily mean outflow from each lake HRU	required	**nlake**	cfs	real	0.0 to 1.0E7	0.1
lake_seep_elev	Elevation over which lakebed seepage to the GWR occurs for lake HRUs using broad-crested weir routing or gate opening routing	broad-crested weir or gate opening routing	**nlake**	real	feet	-300.0 to 10,000.0	1.0
lake_type	Type of lake routing method (1=Puls routing; 2=linear routing; 3=flow through; 4=broad-crested weir; 5=gate opening; and 6=measured flow)	required	**nlake**	none	integer	1 to 6	1

Table 1–11. Input parameters to the Muskingum and Lake Routing Module—muskingum_lake.—Continued

[HRU, hydrologic response unit; GWR, groundwater reservoir; **one**, a constant equal to 1; **nsegment**, number of stream segments; **nmonths**, a constant equal to 12; **nhru**, number of HRUs; **nobs**, number of streamflow gaging stations; **nlake**, number of lake HRUs; **nlakeelev**, maximum number of lake elevations in any rating table; **nratetbl**, number of rating tables for lakes; **ncascade**, total number of connections among HRUs and stream segments; **mxnsos**, maximum number of storage/outflow table values for number of lake HRUs using Puls routing; **nstage**, **nstage2**, **nstage3**, and **nstage4**, maximum number of lake elevations values (rows) for lake rating tables 1, 2, 3, and 4, respectively; ngate, ngate2, ngate3, and ngate4 maximum number of reservoir gate-opening values (columns) for lake rating tables 1, 2, 3, and 4, respectively; cfs, cubic feet per second]

Parameter name	Description	Condition	Dimension	Unit	Type	Range	Default
lake_vol_init	Initial lake volume for each lake using broad-crested weir or gate opening routing	broad-crested weir or gate opening routing	**nlake**	acre-feet	real	0.0 to 10,000.0	0.0
nsos	Number of storage/outflow values in table for each lake using Puls routing	Puls routing	**mxnsos**, **nlake**	none	integer	1 to **mxnsos**	0
o2	Outflow values in outflow/storage tables for each lake using Puls routing	Puls routing	**mxnsos**, **nlake**	cfs	real	0.0 to 100,000.0	0.0
obsin_segment	Index of measured streamflow station that replaces inflow to a segment	required	**nsegment**	none	integer	0 to **nobs**	0
obsout_lake	Index of streamflow measurement station that specifies outflow from each lake using measured flow replacement	**lake_type** = 6	**nlake**	none	integer	0 to **nobs**	0
rate_table	Rating table with stage (rows) and gate opening (cols) for rating table 1 for lakes using gate opening routing and **nratetbl**>0	gate opening routing and **nratetbl** > 0	**nstage**, **ngate**	real	cfs	-100.0 to 1,000.0	5.0
rate_table2	Rating table with stage (rows) and gate opening (cols) for rating table 2 for lakes using gate opening routing and **nratetbl**>1	gate opening routing and **nratetbl** > 1	**nstage**, **ngate**	real	cfs	-100.0 to 1,000.0	5.0
rate_table3	Rating table with stage (rows) and gate opening (cols) for rating table 3 for lakes using gate opening routing and **nratetbl**>2	gate opening routing and **nratetbl** > 2	**nstage**, **ngate**	real	cfs	-100.0 to 1,000.0	5.0
rate_table4	Rating table with stage (rows) and gate opening (cols) for rating table 4 for lakes using gate opening routing and **nratetbl**>3	gate opening routing and **nratetbl** > 3	**nstage**, **ngate**	real	cfs	-100.0 to 1,000.0	5.0
ratetbl_lake	Index of lake associated with each rating table for each lake using gate opening routing	gate opening routing	**nratetbl**	integer	none	0 to **nlake**	0

Table 1–11. Input parameters to the Muskingum and Lake Routing Module—muskingum_lake.—Continued

[HRU, hydrologic response unit; GWR, groundwater reservoir; **one**, a constant equal to 1; **nsegment**, number of stream segments; **nmonths**, a constant equal to 12; **nhru**, number of HRUs; **nobs**, number of streamflow gaging stations; **nlake**, number of lake HRUs; **nlakeelev**, maximum number of lake elevations in any rating table; **nratetbl**, number of rating tables for lakes; **ncascade**, total number of connections among HRUs and stream segments; **mxnsos**, maximum number of storage/outflow table values for number of lake HRUs using Puls routing; **nstage**, **nstage2**, **nstage3**, and **nstage4**, maximum number of lake elevations values (rows) for lake rating tables 1, 2, 3, and 4, respectively; ngate, ngate2, ngate3, and ngate4 maximum number of reservoir gate-opening values (columns) for lake rating tables 1, 2, 3, and 4, respectively; cfs, cubic feet per second]

Parameter name	Description	Condition	Dimension	Unit	Type	Range	Default
runoff_units	Measured streamflow units (0=cfs; 1=cms)	**nobs** > 0	**one**	none	integer	0 or 1	1
s2	Storage values in outflow/storage table for each lake using Puls routing	Puls routing	**mxnsos**, **nlake**	cfs	real	0.0 to 100,000.0	0.0
segment_flow_init	Initial flow in each stream segment	required	**nsegment**	cfs	real	0.0 to 100,000.0	0.0
segment_type	Segment type (0=segment; 1=headwater; 2=lake; 3=replace inflow; 4=inbound to NHM; 5=outbound from NHM; 6=inbound to region; 7=outbound from region; 8=drains to ocean; 9=sink; 10=inbound from Great Lakes; 11=outbound to Great Lakes)	required	**nsegment**	none	integer	0 to 3	0
tbl_gate	Gate openings for each column for rating table 1 for lakes using gate opening routing and **nratetbl**>0	gate opening routing and **nratetbl** > 0	**ngate**	inches	real	0.0 to 20.0	0.0
tbl_gate2	ate openings for each column for rating table 2 for lakes using gate opening routing and **nratetbl**>0	gate opening routing and **nratetbl** > 1	**ngate**	inches	real	0.0 to 20.0	0.0
tbl_gate3	ate openings for each column for rating table 3 for lakes using gate opening routing and **nratetbl**>0	gate opening routing and **nratetbl** > 2	**ngate**	inches	real	0.0 to 20.0	0.0
tbl_gate4	ate openings for each column for rating table 4 for lakes using gate opening routing and **nratetbl**>0	gate opening routing and **nratetbl** > 3	**ngate**	inches	real	0.0 to 20.0	0.0
tbl_stage	Stage values for each row for rating table 1 for lakes using gate opening routing and **nratetbl**>0	gate opening routing and **nratetbl** > 0	**nstage**	feet	real	-100.0 to 1,000.0	5.0
tbl_stage2	Stage values for each row for rating table 2 for lakes using gate opening routing and **nratetbl**>0	gate opening routing and **nratetbl** > 1	**nstage**	feet	real	-100.0 to 1,000.0	5.0

Table 1–11. Input parameters to the Muskingum and Lake Routing Module—muskingum_lake.—Continued

[HRU, hydrologic response unit; GWR, groundwater reservoir; **one**, a constant equal to 1; **nsegment**, number of stream segments; **nmonths**, a constant equal to 12; **nhru**, number of HRUs; **nobs**, number of streamflow gaging stations; **nlake**, number of lake HRUs; **nlakeelev**, maximum number of lake elevations in any rating table; **nratetbl**, number of rating tables for lakes; **ncascade**, total number of connections among HRUs and stream segments; **mxnsos**, maximum number of storage/outflow table values for number of lake HRUs using Puls routing; **nstage**, **nstage2**, **nstage3**, and **nstage4**, maximum number of lake elevations values (rows) for lake rating tables 1, 2, 3, and 4, respectively; ngate, ngate2, ngate3, and ngate4 maximum number of reservoir gate-opening values (columns) for lake rating tables 1, 2, 3, and 4, respectively; cfs, cubic feet per second]

Parameter name	Description	Condition	Dimension	Unit	Type	Range	Default
tbl_stage3	Stage values for each row for rating table 3 for lakes using gate opening routing and **nratetbl**>0	gate opening routing and **nratetbl** > 2	**nstage**	feet	real	-100.0 to 1,000.0	5.0
tbl_stage4	Stage values for each row for rating table 4 for lakes using gate opening routing and **nratetbl**>0	gate opening routing and **nratetbl** > 3	**nstage**	feet	real	-100.0 to 1,000.0	5.0
tosegment	Index of downstream segment to which the segment streamflow flows, for segments that do not flow to another segment enter 0	required	**nsegment**	none	integer	0 to **nsegment**	0
weir_coef	Coefficient for lakes using broad-crested weir routing	broad-crested weir routing	**nlake**	none	real	2.0 to 3.0	2.7
weir_len	Weir length for lakes using broad-crested weir routing	broad-crested weir routing	**nlake**	feet	real	1.0 to 1,000.0	5.0
x_coef	The amount of attenuation of the flow wave, called the Muskingum routing weighting factor; enter 0.0 for reservoirs, diversions, and segment(s) flowing out of the basin	required	**nsegment**	decimal fraction	real	0.0 to 0.5	0.2

[1]If the value of **hru_strmseg_down_id** > 0 for cascade area, this value is ignored.

Table 1–12. Variables used in the Muskingum and Lake Routing Module—muskingum_lake.

[HRU, hydrologic response unit; GWR, groundwater reservoir; **one**, a constant equal to 1; **nhru**, number of HRUs; **nsegment**, number of stream segments; **nexternal**, number of external sources plus destinations; cfs, cubic feet per second]

Variable name	Description	Condition	Input or Output	Dimension	Unit	Type
		Variables input in the Data File				
gate_ht	Height of the gate opening at each dam with a gate	**lake_type** = 5	input	**nratetbl**	inches	real
lake_elev	Elevation of each simulated lake surface	**lake_type** = 4 or 5	input	**nlakeelev**	feet	real
		Computed results				
basin_cfs	Streamflow leaving the basin through the stream network	always	output	**one**	cfs	double
basin_cms	Streamflow leaving the basin through the stream network	always	output	**one**	cms	double
basin_gwflow_cfs	Basin area-weighted average groundwater flow to the stream network	always	output	**one**	cfs	double
basin_hortonian_lakes	Basin area-weighted average Hortonian surface runoff to lakes	**cascade_flag** = 1 and **ncascade** > 0	output	**one**	inches	double
basin_lake_seep	Basin area-weighted average lake-bed seepage to groundwater reservoirs	**lake_type** = 4 or 5	output	**one**	inches	double
basin_lake_stor	Basin volume-weighted average storage for all lakes using broad-crested weir or gate opening routing	always	output	**one**	inches	double
basin_lakeevap	Basin area-weighted average lake evaporation	always	output	**one**	inches	double
basin_lakeinsz	Basin area-weighted average lake inflow from land HRUs	**cascade_flag** = 1 and **ncascade** > 0	output	**one**	inches	double
basin_lakeprecip	Basin area-weighted average precipitation on lake HRUs	always	output	**one**	inches	double
basin_segment_storage	Basin area-weighted average storage in the stream network	**segment_type** = 0, 1, or 3	output	**one**	inches	double
basin_sroff_cfs	Basin area-weighted average surface runoff to the stream network	always	output	**one**	cfs	double
basin_ssflow_cfs	Basin area-weighted average interflow from gravity and preferential-flow reservoirs to the stream network	always	output	**one**	cfs	double
basin_stflow_in	Basin area-weighted average lateral flow entering the stream network	always	output	**one**	inches	double
basin_stflow_mo	Monthly area-weighted average simulated streamflow	always	output	**one**	inches	double
basin_stflow_out	Basin area-weighted average streamflow leaving through the stream network	always	output	**one**	inches	double
din1	Inflow to each lake HRU using Puls or linear storage routing	**lake_type** = 1 or 2	output	**nlake**	cfs	double
flow_out	Total flow out of model domain	always	output	**one**	cfs	double
gw_seep_lakein	Groundwater discharge to each lake HRU for each GWR	**lake_type**= 4 or 5	output	**nhru**	inches	double
hortonian_lakes	Surface runoff to lakes for each HRU	**cascade_flag** = 1 and **ncascade** > 0	output	**nhru**	inches	double
lakein_sz	Cascading interflow and Dunnian surface runoff to lake HRUs for each upslope HRU	**cascade_flag** = 1 and **ncascade** > 0	output	**nhru**	inches	double
lake_2gw	Total seepage from each lake HRU	**lake_type** = 4 or 5	output	**nlake**	cfs	double
lake_evap	Total evaporation from each lake HRU	always	output	**nlake**	inches	double

Table 1–12. Variables used in the Muskingum and Lake Routing Module—muskingum_lake.—Continued

[HRU, hydrologic response unit; GWR, groundwater reservoir; **one**, a constant equal to 1; **nhru**, number of HRUs; **nsegment**, number of stream segments; **nexternal**, number of external sources plus destinations; cfs, cubic feet per second]

Variable name	Description	Condition	Input or Output	Dimension	Unit	Type
lake_inflow	Total inflow to each lake HRU	always	output	**nlake**	cfs	double
lake_interflow	Total interflow into each lake HRU	**cascade_flag** = 1 and **ncascade** > 0	output	**nlake**	cfs	double
lake_invol	Inflow to each lake using broad-crested weir or gate opening routing	**lake_type** = 4 or 5	output	**nlake**	acre-feet	double
lake_lateral_inflow	Lateral inflow to each lake HRU	**cascade_flag** = 1 and **ncascade** > 0	output	**nlake**	cfs	double
lake_outcfs	Streamflow leaving each lake HRU	always	output	**nlake**	cfs	double
lake_outcms	Streamflow leaving each lake HRU	always	output	**nlake**	cms	double
lake_outflow	Evaporation and seepage from each lake HRU	always	output	**nlake**	cfs	double
lake_outvol	Outflow to each lake using broad-crested weir or gate opening routing	**lake_type** = 4 or 5	output	**nlake**	acre-feet	double
lake_precip	Total precipitation into each lake HRU	always	output	**nlake**	cfs	double
lake_seep_in	Total seepage into each lake using broad-crested weir or gate opening routing	lake_type = 4 or 5	output	**nlake**	cfs	double
lake_seepage	Lake-bed seepage from each lake HRU to the associated GWR	**lake_type** = 4 or 5	output	**nlake**	inches	double
lake_seepage_gwr	Net lake-bed seepage to associated GWR	**lake_type** = 4 or 5	output	**nlake**	inches	double
lake_sroff	Total surface runoff into each lake HRU	**cascade_flag** = 1 and **ncascade** > 0	output	**nlake**	cfs	double
lake_sto	Storage in each lake HRU using Puls or linear storage routing	**lake_type** = 1 or 2	output	**nlake**	cfs-days	double
lake_stream_in	Total streamflow to each lake HRU	always	output	**nlake**	cfs	double
lake_vol	Storage for lake HRUs using broad-crested weir or gate opening routing	**lake_type** = 4 or 5	output	**nlake**	acre-feet	double
segment_delta_flow	Cumulative flow in minus flow out for each stream segment	**segment_type** = 0, 1, or 3	output	**nsegment**	cfs	double
seg_gwflow	Area-weighted average groundwater discharge for each segment from HRUs contributing flow to the segment and upstream HRUs	always	output	**nsegment**	inches	double
seg_inflow	Total flow entering a segment	always	output	**nsegment**	cfs	double
seg_lateral_inflow	Lateral inflow entering a segment	always	output	**nsegment**	cfs	double
seg_outflow	Streamflow leaving a segment	always	output	**nsegment**	cfs	double
seg_sroff	Area-weighted average surface runoff for each segment from HRUs contributing flow to the segment and upstream HRUs	always	output	**nsegment**	inches	double
seg_ssflow	Area-weighted average interflow for each segment from HRUs contributing flow to the segment and upstream HRUs	always	output	**nsegment**	inches	double
seg_upstream_inflow	Sum of inflow from upstream segments	always	output	**nsegment**	cfs	double
streamflow_cfs	Streamflow at each measurement station	always	output	**nsegment**	cfs	double
streamflow_cms	Streamflow at each measurement station	always	output	**nsegment**	cfs	double

Surface-Depression Storage Simulation Capability

Simulation of surface-depression storage (DPRST) is used to account for the hydrologic effect of numerous, small, unregulated, water bodies within HRUs. This capability has been enhanced from the implementations described in Viger and others (2010) and Markstrom and others (2015) to provide additional capabilities associated with impervious areas, closed depressions, and flow algorithms. These enhancements include new parameters defining (1) distinctions between surface runoff capture from pervious and impervious fractions of each HRU; (2) distinctions between seepage rates from open and closed depressions; (3) an adjustment factor of evaporation; and (4) the specification of surface-depression area as a fraction of the HRU area.

Five modules include code used in the simulation of surface depressions as the storage and water-holding capacity affects various aspects of the hydrologic cycle. The basin module (`basin`) verifies associated basinwide parameters and sets variables used by the other four modules. The surface runoff modules (`srunoff_smidx` and `srunoff_carea`) include the majority of the DPRST computations, which are surface runoff into and from surface-depression storage, evaporation, interflow, and seepage. The soilzone module (`soilzone`) accounts for evaporation from surface depressions in soil computations. The groundwater flow module (`gwflow`) receives any seepage as input to groundwater storage. The enhancements were accomplished through modifications to the `basin` and surface runoff modules. See Markstrom and others (2015) for descriptions of the surface runoff, soilzone, groundwater flow, and basin modules. Additionally, the `dynamic_param_read` and `water_use_read` modules can be used to dynamically vary the fraction of surface-depression area and average depth for each HRU, and transfer rates and source and destination connectivity, respectively. Inclusion of dynamic parameters and water use for the simulation of surface depressions provides the increased capability to evaluate temporal and spatial trends of the hydrologic effects of historical, current, and projected surface-depression extent and storage volume.

Surface-Depression Simulation Input and Output

The aggregate water-holding capacity and storage of surface depressions of each HRU are simulated as one or two water bodies that are either open (fill and spill) or closed (no lateral outflow). One control parameter (**dprst_flag**) is used to activate surface-depression storage simulation. Surface-depression parameters specify, for each HRU, the fraction of area occupied by the aggregate sum of surface-depression areal extent (**dprst_frac**), average depth of depressions (**dprst_depth_avg**), fraction of depressions that are open (**dprst_frac_open**), interflow routing coefficients for open depressions (**dprst_flow_coef**), initial volume (**dprst_frac_init**), seepage rates from open and closed depressions (**dprst_seep_rate_open** and **dprst_seep_rate_clos**, respectively), fraction of capture of surface runoff generated within each HRU from pervious and impervious areas (**sro_to_dprst_perv** and **sro_to_dprst_imperv**, respectively), fraction of storage at which spill occurs in open depressions (**op_flow_thres**), coefficients to define the average shape for open and closed depressions (**va_open_exp** and **va_clos_exp**, respectively), and evaporation adjustment coefficient (**dprst_et_coef**).

Characterization of surface depressions can use topographic sources, such as digital elevation models, datasets, such as the USGS National Hydrography Dataset (NHD, https://nhd.usgs.gov/data.html) and the U.S. Fish and Wildlife Service National Wetlands Inventory (https://www.fws.gov/wetlands/), and (or) land-use planning maps. A method for using remote sensing information (Landsat scenes: https://www.usgs.gov/science/mission-areas/climate-and-land-use-change/earth-resources-observation-and-science-center?qt-programs_l2_landing_page=0#qt-programs_l2_landing_page) to assess the hydrologic function and characterization of prairie potholes, a type of naturally occurring surface depression, is described in Rover and others (2011). Input parameters used for computation of surface-depression-related processes are defined in table 1–13 and computed variables are defined in table 1–14.

Table 1–13. Input parameters for surface-depression storage computations.

[HRU, hydrologic response unit; **nhru**, number of HRUs; **one**, constant equal to 1]

Parameter name	Description	Dimension	Type	Unit	Range	Default
	Parameter input in the Control File					
dprst_flag	Flag to indicate if surface-depression storage simulation is computed (0=no; 1=yes)	**one**	integer	none	0 or 1	0
	Parameters input in the Parameter File(s)					
dprst_depth_avg	Average depth of surface depressions at maximum water-holding capacity for each HRU	**nhru**	real	inches	0.0 to 500.0	132.0
dprst_et_coef	Fraction of unsatisfied potential evapotranspiration to apply to surface-depression storage for each HRU	**nhru**	real	decimal fraction	0.0 to 1.0	1.0
dprst_flow_coef	Coefficient in linear flow routing equation for open surface depressions for each HRU	**nhru**	real	fraction/day	0.0001 to 0.3	0.05
dprst_frac	Fraction of each HRU area that has surface depressions	**nhru**	real	decimal fraction	0.0 to 0.999 minus **imperv_frac**	0.0
dprst_frac_init	Fraction of maximum surface-depression storage that contains water at the start of a simulation for each HRU	**nhru**	real	decimal fraction	0.0 to 1.0	0.5
dprst_frac_open	Fraction of surface-depression storage area within an HRU that can generate surface runoff as a function of storage volume for each HRU	**nhru**	real	decimal fraction	0.0 to 1.0	1.0
dprst_seep_rate_clos	Coefficient used in linear seepage flow equation for closed surface depressions for each HRU	**nhru**	real	fraction/day	0.0001 to 1.0	0.02
dprst_seep_rate_open	Coefficient used in linear seepage flow equation for open surface depressions for each HRU	**nhru**	real	fraction/day	0.0001 to 1.0	0.02
op_flow_thres	Fraction of open depression storage above which surface runoff occurs; any water above maximum open storage capacity spills as surface runoff for each HRU	**nhru**	real	decimal fraction	0.75 to 1.0	1.0
sro_to_dprst_imperv	Fraction of impervious surface runoff that flows into surface depression storage; the remainder flows to a stream network for each HRU	**nhru**	real	decimal fraction	0.0 to 1.0	0.2
sro_to_dprst_perv	Fraction of pervious surface runoff that flows into surface-depression storage; the remainder flows to a stream network for each HRU	**nhru**	real	decimal fraction	0.0 to 1.0	0.2

Table 1–13. Input parameters for surface-depression storage computations.—Continued

[HRU, hydrologic response unit; **nhru**, number of HRUs; **one**, constant equal to 1]

Parameter name	Description	Dimension	Type	Unit	Range	Default
va_clos_exp	Coefficient in the exponential equation relating maximum surface area to the fraction that closed depressions are full to compute current surface area for each HRU; 0.001 is an approximate rectangle; 1.0 is a triangle	**nhru**	real	none	0.0001 to 1.0	0.001
va_open_exp	Coefficient in the exponential equation relating maximum surface area to the fraction that open depressions are full to compute current surface area for each HRU; 0.001 is an approximate rectangle; 1.0 is a triangle	**nhru**	real	none	0.0001 to 10.0	0.001

Table 1–14. Variables set in surface-depression storage computations.

[HRU, hydrologic response unit; **one**, a constant equal to 1; **nhru**, number of HRUs; GWR, groundwater reservoir]

Variable name	Description	Dimension	Unit	Type
basin_dprst_evap	Basin area-weighted average evaporation from surface-depression storage	**one**	inches	double
basin_dprst_seep	Basin area-weighted average seepage from surface-depression storage	**one**	inches	double
basin_dprst_sroff	Basin area-weighted average surface runoff from open surface-depression storage	**one**	inches	double
basin_dprst_volcl	Basin area-weighted average storage volume in closed surface depressions	**one**	inches	double
basin_dprst_volop	Basin area-weighted average storage volume in open surface depressions	**one**	inches	double
dprst_area_clos	Surface area of closed surface depressions based on storage volume for each HRU	**nhru**	inches	real
dprst_area_open	Surface area of open surface depressions based on storage volume for each HRU	**nhru**	inches	real
dprst_evap_hru	Evaporation from surface depression storage for each HRU	**nhru**	inches	real
dprst_insroff_hru	Surface runoff from pervious and impervious portions into open and closed surface depressions for each HRU	**nhru**	inches	real
dprst_seep_hru	Seepage from surface depression storage to associated GWR for each HRU	**nhru**	inches	double
dprst_sroff_hru	Surface runoff open surface depressions for each HRU	**nhru**	inches	double
dprst_stor_hru	Surface depression storage for each HRU	**nhru**	inches	double
dprst_vol_clos	Storage volume in closed surface depressions for each HRU	**nhru**	acre-inches	double
dprst_vol_clos_frac	Fraction of closed surface-depression storage of the maximum storage for each HRU	**nhru**	decimal fraction	double
dprst_vol_clos_max	Fraction of open surface-depression storage of the maximum storage for each HRU	**nhru**	decimal fraction	double
dprst_vol_open	Storage volume in open surface depressions for each HRU	**nhru**	acre-inches	double
dprst_vol_open_max	Volume of water of open surface-depression storage for each HRU	**nhru**	acre-inches	real

Table 1–14. Variables set in surface-depression storage computations.—Continued

[HRU, hydrologic response unit; **one**, a constant equal to 1; **nhru**, number of HRUs; GWR, groundwater reservoir]

Variable name	Description	Dimension	Unit	Type
dprst_vol_thres_open	Storage volume in open surface depressions above this threshold and below the maximum storage volume (variable *dprst_vol_open_max*) is used to compute	**nhru**	acre-inches	real
hru_sroffi	Surface runoff from impervious areas for each HRU	**nhru**	inches	real
hru_sroffp	Surface runoff from pervious areas for each HRU	**nhru**	inches	real

Surface-Depression Computations

Simulation of surface-depression storage and flow as initially implemented in PRMS is described by Vining (2002, 2004). Viger and others (2010) provides documentation of an enhanced surface-depression simulation implementation as well as techniques for deriving required input information, including the delineation and characterization of surface depressions. Documentation provided in this section of the current report supersedes documentation of the input requirements and equations in Viger and others (2010) and the documentation found in Markstrom and others (2015).

Fractionally, the surface depressions are designated as either open or closed. Each HRU can have open and (or) closed depressions. Closed surface depressions are assumed to have unlimited storage capacity and are not connected to the stream network; that is, they do not spill or produce interflow.

Inflows to surface depressions are rain throughfall, snowmelt, specified fractions of surface runoff generated from pervious and impervious fractions of the HRU, and cascading Hortonian surface runoff from upslope HRUs. Outflows from both open and closed type surface depressions can occur as evaporation and as seepage to groundwater storage. Seepage to groundwater storage is based on specified flow rates. Open surface depressions also generate surface runoff when the volume reaches the specified water-holding capacity threshold and generate interflow at a specified flow rate when the volume reaches a specified threshold that is lower than the water-holding capacity (fill and spill). Surface runoff and interflow are routed to a stream segment associated with the HRU or to associated downslope HRUs and stream segments if the cascading flow option is active. Closed depressions do not generate surface runoff or interflow, which allows the closed depressions to exceed the specified water-holding capacity to approximate geographically isolated areas that can store water without affecting streamflow. Ice cover on surface depressions is not simulated.

The maximum capacity of the surface depressions ($dprst\_vol\_open\_max_{HRU}$ and $dprst\_vol\_clos\_max_{HRU}$) in units of acre-inches is calculated according to

$$dprst\_vol\_open\_max_{HRU} = dprst\_frac\_hru_{HRU} \times \mathbf{hru\_area}_{HRU} \times \mathbf{dprst\_depth\_avg}_{HRU} \times dprst\_frac\_open_{HRU} \text{ and} \quad (35)$$

$$dprst\_vol\_clos\_max_{HRU} = \left(dprst\_frac\_hru_{HRU} \times \mathbf{hru\_area}_{HRU} \times \mathbf{dprst\_depth\_avg}_{HRU}\right) - dprst\_vol\_open\_max_{HRU} . \quad (36)$$

At the start of the simulation (time step 0 or m=0), the initial amount of storage in the surface depressions in acre-inches is set according to

$$dprst\_vol\_open_{HRU}^{m=0} = dprst\_vol\_open\_max_{HRU} \times \mathbf{dprst\_frac\_init}_{HRU} \text{ and} \quad (37)$$

$$dprst\_vol\_clos_{HRU}^{m=0} = dprst\_vol\_clos\_max_{HRU} \times \mathbf{dprst\_frac\_init}_{HRU} . \quad (38)$$

Values of open and closed storage volumes for subsequent time steps are computed on the basis of inflows and outflows and antecedent storage volumes and can be updated by using dynamic parameters. Snowmelt (variable *snowmelt*), computed by the Snow Computation Module, is added directly to open and closed surface depressions as depth, in inches, over the maximum area of the depressions. Additionally, throughfall rain (variable *net_rain*), computed by the Interception Module, is added when there is no snowpack or snowmelt and for mixed precipitation events. These inflows are accumulated and a new storage volume in acre-inches is calculated as

$$dprst\_vol\_open^{m}_{HRU} = dprst\_vol\_open^{m-1}_{HRU} + \left(snowmelt_{HRU} + net\_rain_{HRU}\right) \times dprst\_area\_open^{m-1}_{HRU} \text{ and} \quad (39)$$

$$dprst\_vol\_clos^{m}_{HRU} = dprst\_vol\_clos^{m-1}_{HRU} + \left(snowmelt_{HRU} + net\_rain_{HRU}\right) \times dprst\_area\_clos^{m-1}_{HRU} . \quad (40)$$

Hortonian surface runoff from pervious (variable *hru_sroffp*) and impervious (variable *hru_sroffi*) areas can flow into surface depressions as a proportion of surface runoff generated in an HRU and is added to the volumes computed in equations 39 and 40 according to

$$dprst\_inflow_{HRU} = (srp_{HRU}) \times (hru\_frac\_perv_{HRU}) \times (\mathbf{sro\_to\_dprst}_{HRU}) \times \mathbf{hru\_area}_{HRU} + (sri_{HRU}) \times (\mathbf{hru\_percent\_imperv}_{HRU}) \times (\mathbf{sro\_to\_dprst\_imperv}_{HRU}) \times \mathbf{hru\_area}_{HRU} , \quad (41)$$

$$dprst\_vol\_open^{m}_{HRU} = dprst\_vol\_open^{m}_{HRU} + (dprst\_inflow_{HRU} \times \mathbf{dprst\_frac\_open}_{HRU}) \text{, and} \quad (42)$$

$$dprst\_vol\_clos^{m}_{HRU} = dprst\_vol\_clos^{m}_{HRU} + (dprst\_inflow_{HRU}) \times (1.0 - \mathbf{dprst\_frac\_open}_{HRU}) . \quad (43)$$

After the volumes have been calculated, the corresponding open water-surface area in acres is calculated according to Vining (2002):

$$dprst\_area\_open^{m}_{HRU} = dprst\_area\_open\_max_{HRU} \times e^{(\mathbf{va\_open\_exp}_{HRU}) LOG\left(\frac{dprst\_vol\_open^{m}_{HRU}}{dprst\_vol\_open\_\max_{HRU}}\right)} \text{ and} \quad (44)$$

$$dprst\_area\_clos^{m}_{HRU} = dprst\_area\_clos\_max_{HRU} \times e^{(\mathbf{va\_clos\_exp}_{HRU}) LOG\left(\frac{dprst\_vol\_clos^{m}_{HRU}}{dprst\_vol\_clos\_\max_{HRU}}\right)} . \quad (45)$$

Evaporation lost from both open and closed surface depressions is computed at the potential ET rate (variable *potet*) with an optional adjustment factor applied. However, the maximum amount of evaporation is limited by the unsatisfied potential ET, which is based on the amount of potential ET after accounting for evaporation from the canopy and sublimation from the snowpack (variables *hru_intcpevap* and *snow_evap*, respectively). The amount of evaporation is computed on the basis of the open water-surface area that is limited by the snow-covered area (variable *snowcov_area*), available water in the depressions, and unsatisfied potential ET. Computations are based on the computed surface area, unsatisfied potential ET, the fraction of snow-free surface, and a specified adjustment coefficient, and computations are limited by the total volume of surface-depression storage. Unsatisfied potential ET is computed for open surface depressions, and then closed surface depressions such that the amount of unsatisfied potential ET available for closed surface depressions is reduced by any evaporation from open surface depressions. The potential surface-depression evaporation and actual evaporation from open and closed depressions, in inches, are computed as

$$potet\_dprst\_evap\_hru_{HRU} = MAX[0.0, \text{ or } \begin{pmatrix} (potet_{HRU}(1.0 - snowcov\_area_{HRU}) - \\ hru\_intcpevap_{HRU} - snow\_evap_{HRU} \end{pmatrix} \times \mathbf{dprst\_et\_coef}_{HRU} , \quad (46)$$

$$dprst\_evap\_open_{HRU} = \text{MIN}\begin{bmatrix} potet\_dprst\_evap\_hru_{HRU} , \\ \text{or } dprst\_vol\_open_{HRU} / dprst\_area\_open\_max_{HRU} \end{bmatrix} \text{, and} \quad (47)$$

$$dprst\_evap\_clos_{HRU} = \text{MIN}\begin{bmatrix} potet\_dprst\_evap\_hru_{HRU} - dprst\_evap\_open_{HRU} , \\ \text{or } dprst\_vol\_clos_{HRU} / dprst\_area\_clos\_max_{HRU} \end{bmatrix} . \quad (48)$$

The potential evaporation computed in equation 46 is adjusted by the evaporation from open and closed surface depressions to yield the actual evaporation, in inches, from surface depressions and is computed as

$$dprst\_evap\_hru_{HRU} = (dprst\_evap\_open_{HRU} / dprst\_area\_open\_max_{HRU}) + (dprst\_evap\_clos_{HRU} / dprst\_area\_clos\_max_{HRU}) . \quad (49)$$

The surface-depression volumes computed in equations 42 and 43 are reduced by evaporation loss according to

$$dprst\_vol\_open^{m}_{HRU} = dprst\_vol\_open^{m}_{HRU} - (dprst\_evap\_open_{HRU} \times dprst\_area\_open\_max_{HRU}) \text{ and} \tag{50}$$

$$dprst\_vol\_clos^{m}_{HRU} = dprst\_vol\_clos^{m}_{HRU} - (dprst\_evap\_clos_{HRU} \times dprst\_area\_clos\_max_{HRU}) . \tag{51}$$

Seepage, in inches, to the groundwater reservoirs for each HRU is the sum of seepage from both open and closed surface depressions and is computed as

$$dprst\_seep\_hru_{HRU} = \begin{matrix} \dfrac{\left(dprst\_vol\_open^{m}_{HRU}\right) \times \mathbf{dprst\_seep\_rate\_open}_{HRU}}{\mathbf{hru\_area}_{HRU}} + \\ \dfrac{\left(dprst\_vol\_clos^{m}_{HRU}\right) \times \mathbf{dprst\_seep\_rate\_clos}_{HRU}}{\mathbf{hru\_area}_{HRU}} \end{matrix} . \tag{52}$$

Open surface depressions can produce interflow to the stream network when their storage reaches a threshold volume (variable *dprst_vol_thres_open*). Interflow is computed for water above the threshold volume and less than the maximum storage capacity (*dprst_vol_open_max*). The threshold volume for each HRU is computed according to

$$dprst\_vol\_thres\_open_{HRU} = dprst\_vol\_open\_max_{HRU} \times \left(\mathbf{op\_flow\_thres}_{HRU}\right) . \tag{53}$$

Spillage for open surface depressions occurs when their volume exceeds the maximum storage capacity. The amount of interflow and spillage is summed and included in the surface runoff from the HRU. Surface runoff from open surface depressions for each HRU is computed as

$$spillage_{HRU} = \mathrm{MAX}\begin{bmatrix} 0.0,\text{or} \\ dprst\_vol\_open^{m}_{HRU} - dprst\_vol\_open\_max_{HRU} \end{bmatrix} \text{ and} \tag{54}$$

$$\begin{aligned} dprst\_sroff\_hru_{HRU} = {} & spillage_{HRU} + \\ & \mathrm{MAX}\begin{bmatrix} 0.0,\text{or} \\ dprst\_vol\_open^{m}_{HRU} - spillage_{HRU} - dprst\_vol\_thres\_open_{HRU} \end{bmatrix} . \\ & \times \mathbf{dprst\_flow\_coef}_{HRU} \end{aligned} \tag{55}$$

Then, surface-depression volume computed in equation 50 is adjusted according to

$$dprst\_vol\_open^{m}_{HRU} = dprst\_vol\_open^{m}_{HRU} - dprst\_sroff\_hru_{HRU} . \tag{56}$$

Finally, Hortonian surface runoff from pervious and impervious areas of the HRU is adjusted by the amount of surface runoff that flows to the surface depressions plus any surface runoff from open surface depressions according to

$$hortonian\_flow_{HRU} = srp_{HRU} + sri_{HRU} + \frac{dprst\_sroff\_hru_{HRU} - dprst\_inflow_{HRU}}{\mathbf{hru\_area}_{HRU}} . \tag{57}$$

Initial-Conditions Specification Option

The initial-conditions specification option provides the capability to save the results of a simulation (or spin-up) in a file that can be read as the antecedent conditions required to initiate any number of subsequent (or restart) simulations. The file containing the antecedent conditions is named the Initial Conditions File. This option has been enhanced from previous versions as documented in Leavesley and Stannard (1995), Leavesley and others (1996, 2005), and Markstrom and others (2008) to provide new functionality and correct implementation errors. Implementation in the USGS coupled groundwater and surface-water flow model (GSFLOW, Markstrom and others, 2008) is documented in Regan and others (2015) in which this option is referred to as the restart option.

Hydrologic memory within a model domain is influenced by hydrogeologic and topographic characteristics, dynamic effects of land and water-use changes, complexity of the simulation algorithms, and quality of the input data and can take years to decades to equilibrate with variable climatic conditions. Typically, hydrologic simulation codes set initial values for most states and fluxes to 0.0 with the option to specify some values, such as the water content of various components of the subsurface, lakes, and snowpack. These codes may assume that all states and fluxes will be adequately computed to an equilibrium state within the first year or two of a simulation time period. However, as hydrologic simulation applications expand to regional and national scales, values for initial states and fluxes can be difficult to estimate; a few years may not be adequate to account for hydrologic memory for all processes, such as groundwater storage, and each simulation year can require significant execution time. Typically, some groundwater hydrologic processes require many years to come into equilibrium with the dynamic climate forcing (or stress) data, while surface-water processes respond relatively quickly. As PRMS uses a fairly simple groundwater simulation method, a spin-up simulation of 1 to 3 years may be sufficient to establish antecedent conditions for most restart simulations. For all cases, the spin-up time period should be for a sufficient time period to establish hydrologic conditions for all processes throughout the model domain.

Results from any length spin-up simulation saved in an Initial Conditions File can be used as the antecedent conditions for restart simulations, including another restart simulation; thus, an Initial Conditions File can be read from, and (or) written to, within a single simulation. Each application domain can require different length time periods for spin-up simulations. Typically, the spin-up simulation used to generate an Initial Conditions File has been calibrated and verified for historical conditions.

An example use of the initial-conditions specification option is to execute a spin-up simulation for a 20-year time period to account for hydrologic memory in a large model domain. Such a simulation may generate a set of large output files, in which the majority of values are often ignored. The hydrologic conditions for the last day of the simulation are written to a file, which is read as the antecedent conditions for any number of subsequent restart simulations that require a common set of base-line conditions corresponding to a particular date. Examples of this use are for calibration procedures, sensitivity analyses, and forecasting that can require hundreds to thousands of restart simulations using the same start date. Use of the initial-conditions specification option can greatly reduce execution time because the spin-up simulation is computed once and then is used as antecedent conditions for each restart simulation. The output from these restart simulations is only for the period of interest, which may be smaller and much easier to process and analyze than for the full simulation time period. Reducing the number of simulated years also may reduce the size of required output files, which also reduces execution time.

Specification for Use of the Initial-Conditions File Option

The specification for writing and reading Initial Conditions Files is the same as previous versions of PRMS. Most modules include code related to the initial-conditions specification option, because computed results are saved on the basis of the set of active modules and simulation options for an application. The content and format, now binary, has changed, thus Initial Conditions Files generated by previous versions are not compatible with the current implementation. Two control parameters define the simulation start date (**start_time**) and the simulation end date (**end_time**). Because the values written to an Initial Conditions File represent the hydrologic conditions for the last day of the spin-up simulation, the start date of restart simulations should be the day following the last day of the spin-up simulation.

The restart option is activated by using four control parameters: **init_vars_from_file**, **var_init_file**, **save_vars_to_file**, and **var_save_file** (table 1–15). To read an Initial Conditions File for a restart simulation, specify **init_vars_from_file** equal to `1` and **var_init_file** equal to the pathname of the Initial Conditions File written by a spin-up simulation. To write an Initial Conditions File at the end of a spin-up simulation, specify **save_vars_to_file** equal to `1` and **var_save_file** equal to the pathname of the output Initial Conditions File. Parameter **var_init_file** is not required if **init_vars_from_file** is specified equal to `0`. Likewise, parameter **var_save_file** is not required if **save_vars_to_file** is specified equal to `0`.

A simulation can read from and write to Initial Conditions Files when both **init_vars_from_file** and **save_vars_to_file** are specified equal to `1`. First, the file specified by **var_init_file** is read as the antecedent conditions for the first time step of the restart simulation. Second, the file specified by **var_save_file** is written at the end of the restart simulation. The pathnames specified for the **var_save_file** and **var_init_file** could be the same for simulations that are both a

Table 1–15. Control parameters input for the Initial-Conditions Specification option.

Parameter name	Description	Number	Type	Range	Default
end_time	Simulation end date and time specified in order in the control item as: year, month, day, hour, minute, second	6	integer	user defined	2001, 9, 30, 0, 0, 0
init_vars_from_file	Flag to specify whether or not the Initial Conditions File is specified as an input file (0=no; 1=yes)	1	integer	0 or 1	0
save_vars_to_file	Flag to specify whether or not the Initial Conditions File is specified as an output file (0=no; 1=yes)	1	integer	0 or 1	0
start_time	Simulation start date and time specified in order in the control item as: year, month, day, hour, minute, second	6	integer	user defined	2000, 10, 1, 0, 0, 0
var_init_file[1]	Pathname for Initial Conditions input file	1	character	user defined	prms_ic.in
var_save_file[1]	Pathname for the Initial Conditions File to be generated at end of simulation	1	character	user defined	prms_ic.in

[1]Pathnames can be specified using a maximum of 132 characters

restart and spin-up simulation. This should only be done when the Initial Conditions File read is not needed for any additional restart simulations because it is overwritten at the end of the simulation. Figure 1–7 shows a portion of a Control File to specify reading and writing Initial Conditions Files for the restart option.

Initial Conditions File Compatibility

The values written to an Initial Conditions File represent the conditions for a particular day and set of computation options; thus, these values should be used as the antecedent conditions for a restart simulation that starts the day following the last day of the spin-up simulation with the identical set of computation options. The results for a sequential series are identical to the results of a continuous simulation for the same time period, forcing data, and computation options. A sequential series is a spin-up simulation and is any number of contiguous in-time restart simulations. For example, a series could be an initial spin-up simulation that computes antecedent conditions for the first restart simulation, which computes antecedent conditions for the second restart simulation, which computes antecedent conditions for the third restart simulation, and so on moving forward in time.

Initial Conditions Files are written to and read from using an order based on the computation options selected. As spin-up simulations use a specific set of computation options (including modules) and input, it is recommended that the restart simulation use the identical set of options to avoid possible discontinuities in computed states. However, to provide flexibility the restart option allows some computation options, values of input parameters, and output options to differ between the spin-up and restart simulations. Empirical coefficients and calibration parameters such as interflow, potential evapotranspiration, solar radiation equation coefficients, and temperature and precipitation adjustment factors can differ. However, results using different values for these types of parameters for a pair of spin-up and restart simulations likely will not be the same as a continuous simulation for the same time period.

The simulation code verifies that an Initial Conditions File used for a restart simulation was generated by a spin-up simulation using compatible computation options and discretization as specified in the Control File and dimension values specified in the Parameter File(s). Compatible means that the computation of some hydrologic processes and summary output have multiple options, some of which are independent of one another, and thus can differ between the spin-up and restart simulations. However, results using different computation options for a spin-up and restart-simulation combination likely will not be the same as those for a continuous simulation for the same time period. Note that selection of option alternatives often requires different input parameters. The computation, input, and output options that can differ between spin-up and restart simulations are the following:

- potential evapotranspiration as computed for each HRU, using any combination of modules `potet_jh` (Jensen-Haise method; Jensen and Haise, 1963), `potet_hamon` (Hamon method; Hamon, 1961), `potet_pt` (Priestly-Taylor method; Priestley and Taylor, 1972), `potet_hs` (Hargreaves and Samani method; Hargreaves and Samani, 1982), and `climate_hru` (predistributed values based on any user-defined distribution method) as specified by control parameter **et_module**;

- precipitation computation for each HRU, using any combination of modules `precip_1sta` (based on specified adjustment factors for a specified precipitation measurement from a climate station), `precip_laps` (a computed lapse rate, based on data from two specified precipitation measurements made at different altitudes), `precip_dist2` (specified lapse rates and the inverse of the square of the distance between the centroid of the HRU and the location and data from multiple precipitation measurement stations),

```
Example Control File using pre-processed climate data and Initial
Conditions
####
model_mode
1
4
PRMS
####
start_time
6
1
1980
10
1
0
0
0
####
end_time
6
1
1983
9
1
0
0
0
####
init_vars_from_file
1
1
0
####
var_init_file
1
4
../input/spin_up_ic
####
save_vars_to_file
1
1
1
####
var_save_file
1
4
../output/spin_up_1983_09_01_ic
```

Figure 1–7. Example portion of a Control File for a spin-up simulation.

and climate_hru (pre-distributed values, based on any user-defined distribution method) as specified by control parameter **precip_module**;

- solar radiation computation for each HRU can be computed by using any combination of modules ccsolrad (cloud-cover method) and ddsolrad (degree-day method), as specified by control parameter **solrad_module**;
- transpiration activity for each HRU can be computed by using any combination of modules transp_frost (specify last spring and first killing frost method) and climate_hru (pre-distributed values, based on any user-defined distribution method) as specified by control parameter **transp_module**;
- streamflow computations in the stream network, using any combination of modules strmflow (total streamflow leaving a model domain) and strmflow_in_out (computation of streamflow leaving each stream segment is set to inflow equals outflow) as specified by control parameter **strmflow_module**; and
- output summary options can be different for modules subbasin (summary of select states and fluxes by subbasin), map_results (output files of selected states and fluxes for use as input to other software at select temporal and specified spatial resolution), nhru_summary (output files of selected states and fluxes), prms_summary (summary of basinwide states and fluxes written to a file by using the CSV format, write_climate_hru (output Climate-by-HRU Files based on specified climate distribution options), Statistic Variable and Animation Files, and run-time graphics.

Simulation options that cannot be changed between the spin-up and restart simulations are the following:

- potential evapotranspiration as computed for each HRU by using either the potet_pan (pan evaporation method) or potet_pm (Penman Monteith evaporation method; Penman, 1948) modules as specified by control parameter **et_module**;
- precipitation and air temperature computations for each HRU by using either the xyz_dist (a three-dimensional, multiple-linear regression method, using data from multiple precipitation measurement stations) or ide_dist (an inverse distance and elevation weighting method, using data from multiple precipitation measurement stations) modules as specified by control parameters **precip_module** and **temp_module**;
- temperature computation for each HRU as specified by control parameter **temp_module**;
- transpiration activity for each HRU, using the transp_tindex (temperature index method) module as specified by control parameter **transp_module**;
- surface-depression storage computations as specified by control parameter **dprst_flag** and related parameters;
- streamflow computations in the stream network, using the muskingum (streamflow in each segment computed by using the Muskingum routing method; Linsley and others, 1982) and muskingum_lake (streamflow in each segment computed by using the Muskingum routing method and through each lake computed by using selectable flow-routing methods) modules as specified by control parameter **strmflow_module** and related parameters.

The number of measured values for each type of data (air temperature, precipitation, streamflow, solar radiation, pan evaporation, snow depth, humidity, wind speed, lake-surface elevation, and lake gate openings), which can be specified in the Data File, cannot be changed. That is, the number of measurement stations as specified by the associated dimensions for these data types cannot be changed; if they are, an error message is issued and execution stops. The column order of measured values in a Data File can change, although changing the order is not recommended. The column order in Climate-by-HRU (CBH) Files cannot change because these columns are tied to the HRU identification numbers; however, spin-up and restart simulations can use different combinations of CBH Files as allowed, based on the choice of climate module option requirements listed above.

The values and time period in the Data and CBH Files can be changed. For example, the Data and CBH Files input to a restart simulation can specify only the time period and data values required by the restart simulation and do not include values used in the spin-up simulation; thus, a Data and CBH File used in a restart simulation could be small in comparison to, and have values not included in, a spin-up Data and CBH File. The simulation time period, which is specified by control parameters **start_time** and **end_time**, cannot be longer than, and must be included within, the time period specified in the Data or optional CBH Files. If the specified time period does not meet these requirements, an error message is issued and execution stops.

The values specified in the Parameter and Control Files are read and used for spin-up and restart simulations. Any of these values can differ between a spin-up and restart simulation except for computation, input, and output options as described above and discretization parameters such as elevation, slope, aspect, latitude, type, and area of HRUs, segment connectivity, and cascades. Some HRU-characteristic parameters, such as land-use-related parameters fraction of impervious area, canopy density, and plant cover type, should not be changed because they can create incompatibilities between the antecedent conditions and the restart simulation. These parameters and others, however, can be changed by using the dynamic parameter input option. Some discretization dimensions and parameters are checked for consistency between the Initial Conditions and Parameter Files, including the number of HRUs, lakes, and intersections between HRUs and finite-difference cells, the simulation mode, and whether or not cascades are active. If these differ between the spin-up and restart simulations, an error message is issued and execution stops.

Initial Parameter Values

Parameters that specify initial water content states in the Parameter File(s) are ignored for a restart simulation. These parameters are the initial water content of the capillary reservoir (**soil_moist_init**), recharge zone of the capillary reservoir (**soil_rechr_init**), snowpack water equivalent (**snowpack_init**), gravity reservoir (**ssstor_init**), groundwater reservoir (**gwstor_init**), surface-depression storage fraction (**dprst_frac_init**), the initial density of the snowpack (**den_init**), the initial volume of lakes for lake routing simulations using the broad-created weir or gate opening methods (**lake_vol_init**), the initial surface elevation of lakes for lake routing simulations using the broad-created weir or gate opening methods (**elevlake_init**), the initial storage of lakes for lake routing simulations using the Puls or linear methods (**lake_init**), the initial mean daily outflow of lakes (**lake_qro**), and the initial inflow of lakes for lake routing simulations using the Puls or linear methods (**lake_din1**). A general rule is that parameter names with the suffix "_init" are ignored for a restart simulation.

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Appendix 2. PRMS Apalachicola-Chattahoochee-Flint River Basin Example Application to Demonstrate Use of Dynamic Parameters, Water-Use, Surface-Depression Storage, Streamflow With Lakes, NHRU Summary, and Initial-Conditions Capabilities

Introduction

This appendix describes an example Precipitation Runoff Modeling System version 4 (PRMS-IV) application for simulation of the watershed above the Chattahoochee River near Norcross, Georgia (U.S. Geological Survey [USGS] streamflow-gaging station 02335000). Three new computation options (dynamic parameters, water-use, and NHRU summary) and three updates to existing capabilities (streamflow routing with lakes, surface-depression storage, and initial condition input/output) were tested in this 3,030 kilometer (km^2) watershed. The PRMS application for this example is a subbasin of the Apalachicola-Chattahoochee-Flint River Basin (ACFB) PRMS model developed by LaFontaine and others (2013).

The ACFB includes three major rivers: the Apalachicola, Chattahoochee, and Flint Rivers (fig. 2–1). The Chattahoochee River begins in the mountains of northeastern Georgia and flows southwest through metropolitan Atlanta to the Alabama-Georgia border, where the river flows southward to Lake Seminole on the Florida-Georgia border. The Flint River begins in north-central Georgia, just south of Atlanta, and flows south to Lake Seminole. The Apalachicola River begins at Lake Seminole, which is the confluence of the Chattahoochee and Flint Rivers, and flows southward through Florida to the Gulf of Mexico. The Chattahoochee River is regulated by four U.S. Army Corps of Engineers (USACE) projects and nine run-of-the-river dams (not operated to regulate flow), and the Flint River is relatively unregulated with just two run-of-the-river dams (U.S. Army Corps of Engineers, 1997). The Apalachicola River has one USACE project (Lake Seminole) at its headwaters. The ACFB is nearly half covered with forest, with about one-tenth of the basin being developed (high-, medium-, or low-density) land and just over one-tenth being cultivated crops. The majority of the developed land is in the Chattahoochee River Basin, with most of that attributed to metropolitan Atlanta. Nearly two-thirds of the cultivated cropland is located in the Flint River Basin, almost all of which is located in the lower part of the basin. LaFontaine and others (2013) provides more details about the ACFB setting.

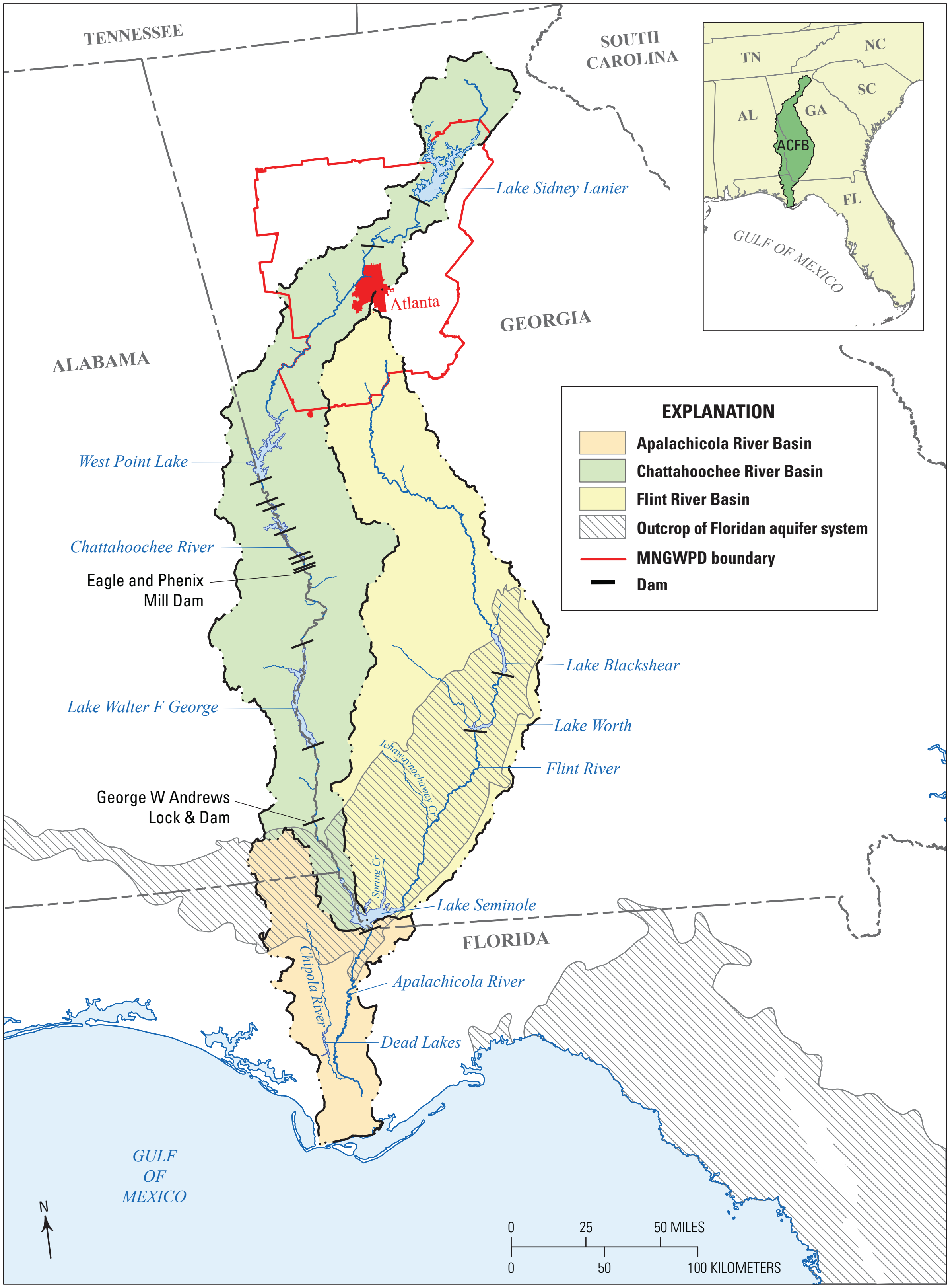
Dynamic parameters characterizing vegetation change and urbanization were developed from work completed as part of the USGS Southeast Regional Assessment Project (Dalton and Jones, 2010). Historical water-use data at site specific locations, primarily in the form of surface-water withdrawals and returns, were obtained from the USGS Site-Specific Water-Use Data System (SWUDS; Mathey, 1990). Surface-depression storage features were parameterized by LaFontaine and others (2013) using Landsat 5 Thematic Mapper imagery. In addition, several main-stem USACE projects are located in the ACFB but were not simulated as lakes with changing storage and regulated releases in the published version of the ACFB PRMS model (LaFontaine and others, 2013). The Lake Sidney Lanier reservoir was simulated two ways: as a flowthrough lake where flow in equaled flow out and using flow substitution with observed streamflow at the lake outlet. Each of these enhancements allows for simulations to approximate actual flows instead of the historical PRMS simulations that computed "natural" or "unimpacted" flows.

Dynamic Parameters Input

The dynamic parameters module was tested with various realizations of urbanization based on decadal slices from 2010 to 2080 developed using the Slope, Land use, Exclusion, Transportation, and Hillshade (SLEUTH; Clarke and Gaydos, 1998; Clarke, 2008) modeling software. Land-cover characteristics for year 2000 were used as the base case for each model. Projections of urbanization from SLEUTH were used to develop values of the parameter **hru_percent_imperv**. To compress the example simulations, the application years for the realizations of **hru_percent_imperv** were changed from 2010–2080 to 1982–1998 to demonstrate the functionality of the model. The original simulations that used these projections were completed by LaFontaine and others (2015). The model input and output files for this example simulation are provided in Regan and LaFontaine (2017).

Water-Use Data

Historical water-use data consisting of monthly withdrawals were incorporated into the ACFB PRMS application for the upper Chattahoochee River Basin (fig. 2–2). Public water-supply water-use data (withdrawals and returns) were retrieved from the USGS SWUDS, and each location was assigned to the applicable stream segment in the PRMS application for the year 1998. Water-withdrawal locations that were on streams not included in the model stream network were assigned to the model stream segment that eventually receives the flow from that stream. The simulated streamflow summarized at the downstream end of each stream segment is assumed to be a valid representation of these locations. The destination of each withdrawal was assigned as consumptive use. The model input and output files for this example simulation are provided in Regan and LaFontaine (2017).



Base modified from U.S. Geological Survey 1:2,000,000-scale digital data, 1990–1994

Figure 2–1. Map showing the location of the Apalachicola-Chattahoochee-Flint River Basin (from LaFontaine and others, 2013).

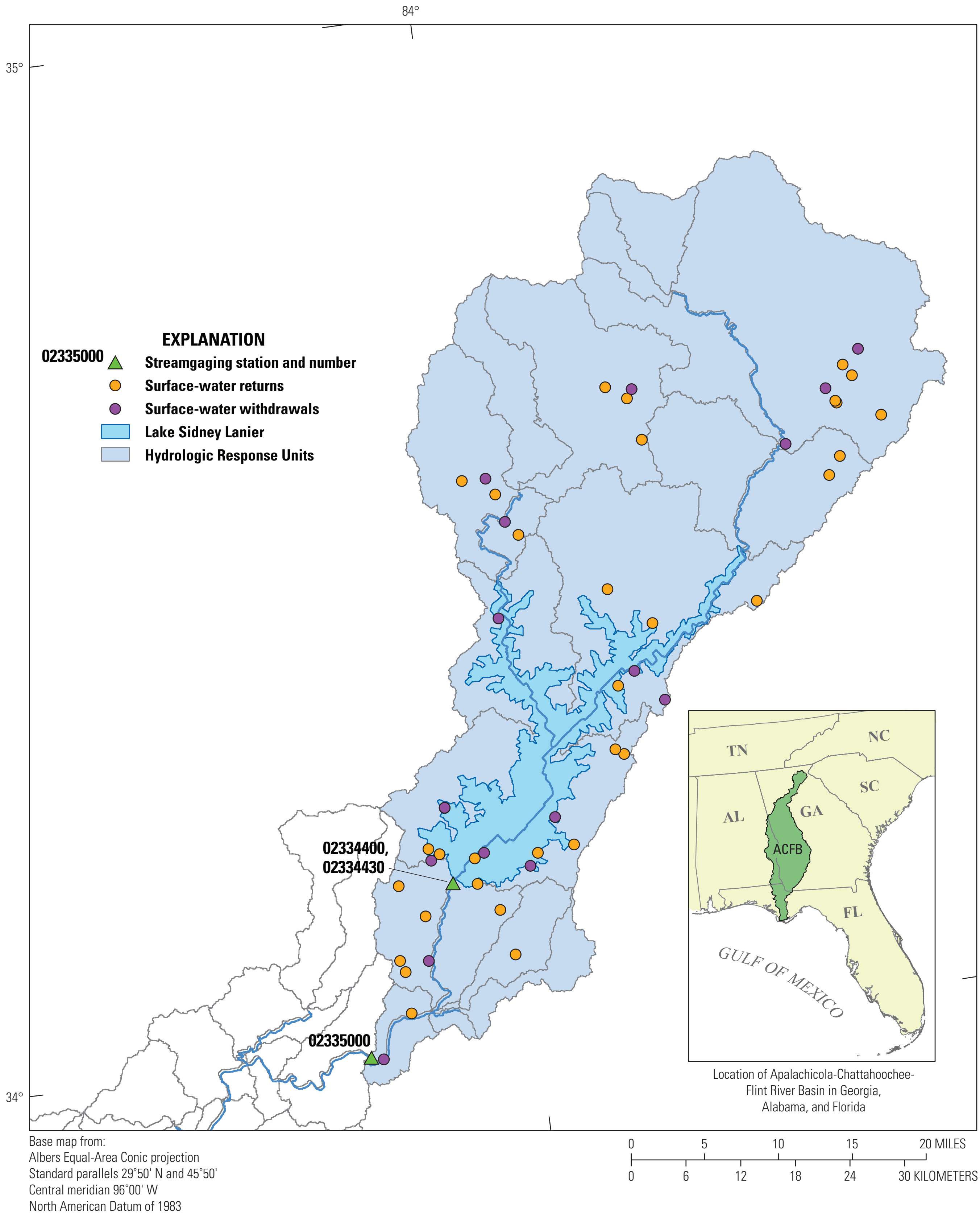


Figure 2–2. Map of the upper Chattahoochee River Basin showing streamflow-gaging stations, water withdrawal locations, and Lake Sidney Lanier.

Surface-Depression Storage

Simulation of surface-depression storage was included in the ACFB application of PRMS documented in LaFontaine and others (2013), using a previous version of the surface-depression storage simulation option. These surface depressions were mapped from Landsat 5 Thematic Mapper imagery for the ACFB (https://landsat.usgs.gov/; accessed September 9, 2014) and parameterized for use in PRMS. This coverage of surface depressions was found to be generally more complete for smaller features than the water-body datasets contained in the National Hydrography Dataset (https://nhd.usgs.gov/; accessed September 9, 2014) or the National Wetlands Inventory (https://www.fws.gov/wetlands/; accessed September 9, 2014). The ACFB PRMS model was converted to the current surface-depression storage simulation configuration, and the parameters **dprst_et_coef** and **sro_to_dprst_imperv** were added to the model parameter file; these parameters are described in table 1-13 in appendix 1 of this report. The model input and output files for this example simulation are provided in Regan and LaFontaine (2017).

Streamflow Routing With On-Channel Lakes

The upper Chattahoochee River part of the ACFB above streamflow-gaging station 02335000 (Chattahoochee River near Norcross, GA; fig. 2) was used to test the Streamflow Routing with Lakes module `muskingum_lake`. Lake Sidney Lanier, located in this part of the ACFB, is a substantial reservoir with a drainage area of 1,040 square miles constructed in 1958 by the USACE for flood control, recreation, and water supply (fig. 1). Two example configurations of lake simulations are included in this report, the flowthrough option and the flow replacement option. Outflow from Lake Sidney Lanier was simulated by using observed streamflow data from USGS streamflow-gaging station 02334430 (Chattahoochee River at Buford Dam, near Buford, GA; fig. 2). The model input and output files for this example simulation are provided in Regan and LaFontaine (2017).

HRU Summary Option

In many cases, users of PRMS want to use time series spatial distributions of specific model variables, such as runoff, soil moisture, or recharge, for analysis purposes. In past applications, this information could only be obtained by substantial editing of the Control File to output a statvar file with all the pertinent information, or by using the animation file. See Markstrom and others (2015) for a description of the statvar and animation file types. This enhancement was tested in the ACFB by outputting the components of streamflow (surface runoff [variable *sroff*], shallow subsurface flow [variable *ssres_flow*], groundwater flow [variable *gwres_flow*]), recharge to the groundwater reservoir (variable *recharge*), and soil moisture (variable *soil_moist*) for each Hydrologic Response Unit (HRU) in the ACFB PRMS model. These variables are described in appendix 1 of Markstrom and others (2015). The model input and output files for this example simulation are provided in Regan and LaFontaine (2017).

Initial Conditions Option

For applications where the same condition is used repeatedly as the start of a forecast or a scenario, and the model execution up to that point is fairly time/computation intensive, this initial condition option can eliminate model spin-up time to that starting point. For this application, which currently simulates hydrologic response of the ACFB for the period January 1, 1950 to September 30, 1999, the date September 30, 1983 was chosen as the desired initial condition. Testing of this option was accomplished by comparing the hydrologic response for the period October 1, 1983 to September 30, 1999 for simulations which were run for the period October 1, 1980 to September 30, 1999 with those which were run only for October 1, 1983 to September 30, 1999, using the initial conditions from September 30, 1983 as the starting point. The model input and output files for this example simulation are provided in Regan and LaFontaine (2017).

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Manuscript was approved June 1, 2017

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Prepared by the USGS Science Publishing Network, Reston Publishing Service Center
Edited by Kay P. Naugle
Layout by Cathy Knutson

Regan and LaFontaine—**Documentation of Modules and Updates to Specification Options With the Precipitation-Runoff Modeling System**—Techniques and Methods 6–B8

ISSN 2328-7055 (online)
https://doi.org/10.3133/tm6B8