

## GSFLOW Release Notes

**Version 2.2.0** – February 18, 2021

<https://doi.org/10.5066/P9D8AFBT>

This file describes changes to GSFLOW with each official release. Modules, file names, utility routines, and user input are identified by using `Courier New` font. Input parameters and dimensions are identified by using **bold** font. State and flux variables are identified by using *italic* font. GSFLOW can be used to run PRMS-only and MODFLOW-only simulations (that is, non-integrated simulations) in addition to the integrated GSFLOW mode. This version is based on MODFLOW-NWT version 1.2, MODFLOW-2005 version 1.12.0, and PRMS version 5.2.0.

This major release (GSFLOW version 2.2.0) adds new functionality for: 1) glacier dynamics, 2) continuous frozen ground dynamics, and 3) the distribution of air temperature and precipitation. New module `glacr_melt` and associated major changes and enhancements to module `snowcomp` allow for improved simulation of glaciers. Glacier dynamics and two examples are described in Van Beusekom and Viger (2015). Continuous frozen ground (CFG) dynamics were added, which involved changes to modules `soilzone`, `srunoff_carea`, and `srunoff_smidx`. The CFG method is described in Mastin (2009). New modules `temp_map` and `precip_map` allow for the distribution of air temperature and precipitation on the basis of area-weighted mapping from input datasets, such as a gridded data set.

There have been numerous changes to the `stream_temp` module since the previous release to address bugs. These include improved calculations of: 1) stream temperatures from stream flow coming from upstream segments; 2) water temperatures from lateral flows from adjacent land surfaces (i.e. lateral components of flow from adjacent HRUs); and 3) water temperatures due to the daily energy fluxes on the stream segments. This version of the `stream_temp` module will give significantly different simulation results than previous versions of the module. Any modeling work done with previous versions of this module should be redone with this (or subsequent) releases. Minor changes were made to several PRMS and GSFLOW modules to improve code readability.

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## ABSTRACT

GSFLOW is a coupled Groundwater and Surface-Water Flow model based on the integration of the U.S. Geological Survey Precipitation-Runoff Modeling System (PRMS; Markstrom and others, 2015) and the U.S. Geological Survey Modular Groundwater Flow Model (MODFLOW-2005, Harbaugh, 2005; MODFLOW-NWT, Niswonger and others, 2011). In addition to the basic PRMS and MODFLOW simulation methods, several additional simulation methods were developed and existing PRMS modules and MODFLOW packages were modified to facilitate integration of the models. Methods were developed to route flow between the PRMS Hydrologic Response Units (HRUs) and the MODFLOW finite-difference cells, and between HRUs and streams and lakes. The modular programming structure of PRMS and MODFLOW support integration while retaining independence.

GSFLOW simulates coupled groundwater/surface-water flow in one or more watersheds. Simulations integrate flow across the land surface, within subsurface saturated and unsaturated materials, and within streams and lakes. Required inputs include: 1) climate data (measured or estimated precipitation, maximum and minimum air temperature, and depending on climate distribution options selected, solar radiation, potential evapotranspiration, humidity, and wind speed), 2) groundwater stresses (such as withdrawals) and 3) boundary conditions to account for inflows to and outflows from the modeled region (such as streamflow and heads). GSFLOW simulations can be used to evaluate the effects of land-use change, climate variability, and groundwater withdrawals on surface and subsurface flow. The model incorporates well documented methods for simulating runoff and infiltration from precipitation; balancing energy and mass budgets of the plant canopy, snowpack, and soil zone; and simulating the interaction of surface-water and groundwater in watersheds. The spatial and temporal domain of GSFLOW simulations can range from a few square kilometers to several thousand square kilometers, over time periods that range from months to several decades. An important aspect of GSFLOW is its ability to conserve water mass and to provide comprehensive water budgets.

GSFLOW allows three simulation modes—coupled (GSFLOW and GSFLOW5), PRMS-only (PRMS and PRMS5), and MODFLOW-only (MODFLOW). The capability of having PRMS-only and MODFLOW-only simulations in GSFLOW allows incremental model setup that provides flexibility in model calibration.

GSFLOW operates on a daily time step. The MODFLOW variable-length stress period is retained so that changes in stress or boundary conditions can be specified on any time step. Only the first stress period can be designated as steady for integrated simulations. No computations pertaining to PRMS are executed for an initial steady-state stress period. While PRMS computations always operate on a daily time step, MODFLOW-only simulations support time steps other than daily, and the user can specify the time step length within the MODFLOW discretization input file. There have been several applications of GSFLOW to real-world systems since the initial release of the software in 2008. Many of these applications are referenced on

the USGS GSFLOW webpage (<https://www.usgs.gov/software/coupled-ground-water-and-surface-water-flow-model-gsflow>).

## SYSTEM REQUIREMENTS

GSFLOW is written in the Fortran 95 and C programming languages. The code has been used on personal computers running various versions of the Microsoft Windows operating system and Linux based computers. A typically small model, e.g., around 100 Hydrologic Response Units (HRUs)/grid cells can be executed on almost all computers. Large models, e.g., greater than 100,000 HRUs/grid cells may need at least 8 GB of RAM to run effectively. Executables provided in this release are built to run on 64-bit computers.

## INPUT-FILE INSTRUCTIONS

Instructions for preparing input files for GSFLOW were provided with the first release of GSFLOW as Appendix 1 in Markstrom and others (2008). Since that time, new functionality has been added to the software; parameters and variables have been added, modified, and deleted; and some of the original functionality has been removed. As a result, it has been necessary to update the original input instructions with each new release of GSFLOW. The file `GSFLOW_Input_Instructions.v.2.2.0.pdf` is located in the “doc” subdirectory of the GSFLOW release. This file includes descriptions and tables for GSFLOW and PRMS modules and MODFLOW packages available in GSFLOW, as well as GSFLOW-specific input parameters and output variables. Input instructions provided in this file supersede some of the information found in Appendix 1 in Markstrom and others (2008), which provides a general discussion of the terminology, styles, and formats of GSFLOW inputs and the definitions of each of the GSFLOW input files.

Instructions for preparing PRMS input files can be found in the PRMS-IV documentation report (Markstrom and others, 2015; <https://pubs.usgs.gov/tm/6b7/>) and the file `PRMS_tables_5.2.pdf`, which is located in the “doc\Related reports” subdirectory of this release, provides updated tables from the PRMS-IV documentation report. These updated tables describe PRMS modules, dimensions for parameters and variables, parameters in the Control File, parameters in the Parameter File, and input and output variables. A highlight-color-coding system in `PRMS_tables_5.2.pdf` indicates which PRMS version a change was made from PRMS version 4.0.3—**red** for PRMS-5.2.0, **pink** for PRMS 5.1.0, and **green** for PRMS-5.0.0.

Instructions for preparing MODFLOW input files for all MODFLOW-2005 and MODFLOW-NWT Packages and Processes are provided in the *Online Guide to MODFLOW-2005* (<https://water.usgs.gov/ogw/modflow/MODFLOW-2005-Guide/>) and *Online Guide to MODFLOW-NWT* (<https://water.usgs.gov/ogw/modflow-nwt/MODFLOW-NWT-Guide/>). Updated input instructions for the SFR2, UZF1, and AG Package are included in the “doc” subdirectory of the GSFLOW release.

## DOCUMENTATION AND ADDITIONAL RESOURCES

### GSFLOW Online Documentation:

<https://www.usgs.gov/software/coupled-ground-water-and-surface-water-flow-model-gsflow>

### GSFLOW Primary Documentation:

Markstrom, S.L., Niswonger, R.G., Regan, R.S., Prudic, D.E., and Barlow, P.M., 2008, GSFLOW—Coupled ground-water and surface-water flow model based on the integration of the precipitation-runoff modeling system (PRMS) and the modular ground-water flow model (MODFLOW–2005): U.S. Geological Survey Techniques and Methods, book 6, chap. D1, 240 p., <https://pubs.usgs.gov/tm/tm6d1/>. This report has been included as file `tm6d1_GSFLOW.pdf` in the “doc” subdirectory of this release. Note that input instructions included in this report are out of date, and users should refer to other sources for input instructions described in these release notes. The primary documentation report for the PRMS is Markstrom and others (2015). The primate documentation report for MODFLOW-NWT is Niswonger and others (2011).

### Additional MODFLOW and PRMS Documentation:

PDFs of the reports listed below are provided in the “doc\Related reports” subdirectory of this release.

Harbaugh, A.W., 2005, MODFLOW-2005, the U.S. Geological Survey modular ground-water model--the Ground-Water Flow Process: U.S. Geological Survey Techniques and Methods 6-A16, variously paginated. <https://pubs.usgs.gov/tm/2005/tm6A16/>. File `tm6a16_MF2005.pdf`.

Henson, W.R., Medina, R.L., Mayers, C.J., Niswonger, R.G., and Regan, R.S., 2013, CRT—Cascade routing tool to define and visualize flow paths for grid-based watershed models: U.S. Geological Survey Techniques and Methods, book 6, chap. D2, 28 p., <https://pubs.usgs.gov/tm/tm6d2/>. File `tm6d2_CRT.pdf`.

Markstrom, S.L., Regan, R.S., Hay, L.E., Viger, R.J., Webb, R.M.T., Payn, R.A., and LaFontaine, J.H., 2015, PRMS-IV, the precipitation-runoff modeling system, version 4: U.S. Geological Survey Techniques and Methods, book 6, chap. B7, 158 p., <https://dx.doi.org/10.3133/tm6B7>. File `tm6b7_PRMS-IV.pdf`.

Mastin, M.C., 2009, Watershed models for decision support for inflows to Potholes Reservoir, Washington: U.S. Geological Survey Scientific Investigations Report 2009–5081, 54 p., <https://pubs.usgs.gov/sir/2009/5081/pdf/sir20095081.pdf>. File `sir20095081_cfigi.pdf`.

Niswonger, R.G., Panday, Sorab, and Ibaraki, Motomu, 2011, MODFLOW-NWT, A Newton formulation for MODFLOW-2005: U.S. Geological Survey Techniques and Methods 6-A37, 44 p. <https://pubs.usgs.gov/tm/tm6a37/>. File tm6a37\_NWT.pdf.

Niswonger, R.G., Prudic, D.E., and Regan, R.S., 2006, Documentation of the Unsaturated-Zone Flow (UZF1) Package for modeling unsaturated flow between the land surface and the water table with MODFLOW-2005: U.S. Geological Survey Techniques and Methods 6-A19, 62 p. File tm6a19\_UZF.pdf.

Niswonger, R.G., and Prudic, D.E., 2005, Documentation of the Streamflow-Routing (SFR2) Package to include unsaturated flow beneath streams—A modification to SFR1: U.S. Geological Survey Techniques and Methods 6-A13, 50 p. File tm6a13\_SFR.pdf.

Niswonger, R. G., 2020, An Agricultural Water Use Package for MODFLOW and GSFLOW. Environmental Modelling & Software, 104617. File AG\_Package\_EM&S.pdf.

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>. File tm6b8\_PRMS\_enhancements.pdf.

Regan, R.S., Markstrom, S.L., Hay, L.E., Viger, R.J., Norton, P.A., Driscoll, J.M., LaFontaine, J.H., 2018, Description of the National Hydrologic Model for use with the Precipitation-Runoff Modeling System (PRMS): U.S. Geological Survey Techniques and Methods, book 6, chap B9, 38 p., <https://doi.org/10.3133/tm6B9>. File tm6b9\_nhm\_prms.pdf.

Regan, R.S., Niswonger, R.G., Markstrom, S.L., and Barlow, P.M., 2015, Documentation of a restart option for the U.S. Geological Survey coupled groundwater and surface-water flow (GSFLOW) model: U.S. Geological Survey Techniques and Methods, book 6, chap. D3, 19 p., <https://dx.doi.org/10.3133/tm6D3/>. File tm6d3\_Restart.pdf.

Sanders, M.J., Markstrom, S.L., Regan, R.S., and Atkinson, R.D., 2017, Documentation of a daily mean stream temperature module—An enhancement to the Precipitation-Runoff Modeling System: U.S. Geological Survey Techniques and Methods, book 6, chap. D4, 18 p., <https://doi.org/10.3133/tm6D4>. File tm6d4\_stream\_temp.pdf.

Van Beusekom, A.E., and Viger, R.J., 2015, A glacier runoff extension to the Precipitation Runoff Modeling System, Journal of Geophysical Research: Earth Science, 21 p., <https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2015JF003789>. File glacier\_2016\_VanBeusekom.pdf.

Documentation and additional resources for PRMS and MODFLOW are available at <https://www.usgs.gov/software/precipitation-runoff-modeling-system-prms> and

<https://www.usgs.gov/mission-areas/water-resources/science/modflow-and-related-programs>, respectively.

Bakker, Mark, Schaars, Frans, Hughes, J.D., Langevin, C.D., and Dausman, A.M., 2013, Documentation of the seawater intrusion (SWI2) package for MODFLOW: U.S. Geological Survey Techniques and Methods, book 6, chap. A46, 47 p.

Bedekar, Vivek, Morway, E.D., Langevin, C.D., and Tonkin, Matt, 2016, MT3D-USGS version 1: A U.S. Geological Survey release of MT3DMS updated with new and expanded transport capabilities for use with MODFLOW: U.S. Geological Survey Techniques and Methods 6-A53, 69 p., <http://dx.doi.org/10.3133/tm6A53>.

Gardner, M. A., Morton, C. G., Huntington, J. L., Niswonger, R. G., & Henson, W. R., 2018, Input data processing tools for the integrated hydrologic model GSFLOW: Environmental modelling & software, 109, 41-53.

Leavesley, G.H., Lichty, R.W, Troutman, B.M., and Saindon, L.G., 1983, Precipitation-runoff modeling system--User's manual: U.S. Geological Survey Water-Resources Investigations Report 83-4238, 207 p. <https://pubs.usgs.gov/wri/1983/4238/report.pdf>.

Leavesley, G.H., Restrepo, P.J., Markstrom, S.L., Dixon, M., and Stannard, L.G., 1996, The Modular Modeling System (MMS): User's manual: U.S. Geological Survey Open-File Report 96-151, 142 p. <https://pubs.usgs.gov/of/1996/0151/report.pdf>.

Viger, R.J., Hay, L.E., Jones, J.W., and Buell, G.R., 2010, Effects of including surface depressions in the application of the Precipitation-Runoff Modeling System in the Upper Flint River Basin, Georgia: U.S. Geological Survey Scientific Investigations Report 2010-5062, 36 p. <https://pubs.usgs.gov/sir/2010/5062/pdf/SIR10-5062.pdf>.

## FUNCTIONALITY, Version 2.2.0

**PRMS Modules and Utility Routines** [listed in computation order; all are modules and written in the FORTRAN programming language, unless noted; yellow highlight designates new modules and utilities for this version (2.2.0)]. Note, additional modules and routines can be easily added that are written in FORTRAN, C, and other languages that can be linked to those languages.

<code>prms_constants</code>	.f90	Defined Constants (Initialization Utility)
<code>mmf</code>		Data-Structure and Utility Routines (written in the C language)
<code>basin</code>		Basin Module
<code>climateflow</code>		Climate and Flow Parameters and Variables Input (Utility Routine)
<code>cascade</code>		Cascading-Flow Module
<code>obs</code>		Observed-Data Module

dynamic_param_read	Dynamic Parameter Input Module
water_use_read	Water-Use Input Module
prms_time	Time Variable Computation (Utility Routine)
soltab	Potential Solar-Radiation Module
temp_1sta	One-Station Air-Temperature-Distribution Module
temp_laps	Lapse-Station Air-Temperature-Distribution Module
temp_dist2	Inverse-Distance Air-Temperature-Distribution Module
temp_map	Area-Weighted Mapping of Input Temperature Data Module
temp_sta	Station Air-Temperature-Distribution Module
precip_1sta	One-Station Precipitation-Distribution Module
precip_laps	Lapse-Station Precipitation-Distribution Module
precip_map	Area-Weighted Mapping of Input Precipitation Data Module
precip_dist2	Inverse-Distance Precipitation-Distribution Module
xyz_dist	Multiple Linear Regression Precipitation and Temperature-Distribution Module
ide_dist	Inverse Distance and Elevation Precipitation and Temperature-Distribution Module
climate_hru	Pre-computed and Distributed Climate Module
ddsolrad	Degree-Day Solar-Radiation Distribution Module
ccsolrad	Cloud-Cover Solar-Radiation Distribution Module
potet_jh	Jensen-Haise Potential-Evapotranspiration Module
potet_hamon	Hamon Potential-Evapotranspiration Module
potet_pan	Pan-Evaporation Potential-Evapotranspiration Module
potet_hs	Hargreaves and Samani Potential-Evapotranspiration Module
potet_pt	Priestly–Taylor Potential-Evapotranspiration Module
potet_pm	Penman–Monteith Potential-Evapotranspiration Module that uses wind-speed and humidity data specified in CBH Files
potet_pm_sta	Penman–Monteith Potential-Evapotranspiration Module that uses wind-speed and humidity data specified in the PRMS Data File
transp_frost	Frost Based Active Transpiration Period Module
frost_date <sup>1</sup>	Preprocess Spring and Fall Frost Module
transp_tindex	Temperature Index Based Active Transpiration Period Module
intcp	Precipitation-Interception Module
snowcomp	Snow Dynamics Module
glacr_melt	Glacier Dynamics Module
srunoff_smidx	Nonlinear source Area Surface-Runoff and Infiltration Module
srunoff_carea	Linear Source Area Surface-Runoff and Infiltration Module
soilzone	Soil-Zone Module
gwflow <sup>1</sup>	Ground-Water Reservoir Module
subbasin	Subbasin Module
routing <sup>1</sup>	Stream Network Computations Routing (Utility Routine)
strmflow <sup>1</sup>	Streamflow Module
muskingum <sup>1</sup>	Muskingum Streamflow Routing Module



muskingum_mann <sup>1</sup>	Muskingum Streamflow Routing using Manning's N Module
strmflow_in_out <sup>1</sup>	Streamflow routing with inflow equals outflow for each segment
muskingum_lake <sup>1</sup>	Muskingum Streamflow and Lake Routing Module
stream_temp <sup>1</sup>	Stream Network Temperature Module
water_balance	Water Balance Debug (Utility Routine)
nhru_summary	Write User-Selected HRU-based Variables to CSV File Module
nsegment_summary	Write User-Selected Stream Segment Variables to CSV File Module
nsub_summary	Write User-Selected Subbasin Variables and HRU-based Variables Summarized by Subbasins to CSV File Module
basin_summary	Write User-Selected Basin Variables to CSV File Module
prms_summary <sup>1</sup>	PRMS Summary Module
basin_sum <sup>1</sup>	Watershed Flow-Summary Module
map_results	Map Based Output Module
write_climate_hru <sup>1</sup>	Generate Climate-by-HRU Files Preprocess Module
convert_params	Generate PRMS-IV or PRMS-V Parameters Preprocess Module

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<sup>1</sup>This module is used for PRMS-only simulations.

<sup>2</sup>Note that the names of PRMS modules are different than those shown in the GSFLOW manual (TM 6-D1) and in previous release notes. A warning message is printed if an old name is used, but the code is downward compatible, so users do not need to change the old module names.

### GSFLOW Modules

gsflow_prms	Computational-Sequence Control for PRMS and GSFLOW
gsflow_modflow	Computational-Sequence Control for MODFLOW Module
gsflow_prms2mf	PRMS to MODFLOW Integration Module
gsflow_mf2prms	MODFLOW to PRMS Integration Module
gsflow_budget	Watershed-Budget Summary Module
gsflow_sum	Flow-Components Summary Module

### MODFLOW Packages

The Geometric Multi-Grid (GMG) Solver Package is not included in this version of GSFLOW; it is available in version 1.2.1.

BAS	Basic Package
BCF	Block-Centered Flow Package
UPW	Upstream-Weighting Flow Package
LPF	Layer-Property Flow Package
HUF	Hydrogeologic-Unit Flow Package
HFB	Horizontal Flow Barrier Package
DRN <sup>1</sup>	Drain Package

DRT <sup>1</sup>	Drain and Return Flow Package
ETS <sup>1</sup>	Evapotranspiration Segments Package
EVT <sup>1</sup>	Evapotranspiration Package
IBS <sup>1</sup>	Interbed Storage Package
RCH <sup>1</sup>	Recharge Package
WEL	Well Package
GHB	General Head Boundary Package
FHB	Flow and Head Boundary Package
CHD	Time-Variant Specified-Head Option
RES <sup>1</sup>	Reservoir Package
RIV <sup>1</sup>	River Package
STR <sup>1</sup>	Stream Package
SWR <sup>1</sup>	Surface-Water Routing Package
SUB <sup>1</sup>	Subsidence Package
UZF	Unsaturated-Zone Flow Package
SFR	Streamflow-Routing Package
LAK	Lake Package
AG	Agriculture Package
GAG	Gage Package
MNW1	Version 1 of the Multi-Node Well Package
MNW2	Version 2 of the Multi-Node Well Package
SWI <sup>1</sup>	Sea Water Intrusion Package
SWT <sup>1</sup>	Subsidence for Water-Table Package
SIP	Strongly Implicit Procedure Package
DE4	Direct Solver Package
PCG	Preconditioned-Conjugate Gradient Package
NWT	Newton Solver Package
LMT <sup>1</sup>	Link MT3DMS Package
OBS	Observation Process (BAS, CHD, GHB, DRN <sup>1</sup> , RIV <sup>1</sup> , STR <sup>1</sup> )

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<sup>1</sup>This package is used for MODFLOW-only simulations.

## FREQUENTLY ASKED QUESTIONS:

### CLARIFICATION ON GSFLOW FUNCTIONALITY FOR SIMULATIONS WITH `modflow_time_zero` NOT EQUAL TO `start_time`

The restart option for GSFLOW (Regan and others, 2015) provided a capability to start a model for a time that follows the beginning of the stress period data defined in MODFLOW input packages. Non-restart simulations also can have a starting time that is later than the first stress period defined in MODFLOW. Thus, a GSFLOW simulation could start at a time that is after the first stress period defined in MODFLOW. This condition requires the user to define the Control

parameters **modflow\_time\_zero** and **start\_time** that are the date (year, month, day) that defines the time of the first stress period in MODFLOW and time the simulation starts, respectively. Having a **modflow\_time\_zero** that is different than **start\_time** impacts the meaning of several MODFLOW variables that are used for referencing time in a simulation and for output control. These variables include the stress period (KPER), time step (KSTP), total time (TOTIM), and stress period time (PERTIM). Definitions are provided here for clarification on these variables for simulations when **modflow\_time\_zero** is not equal to **start\_time**. The values of KPER and KSTP have implications throughout MODFLOW packages, for example, the OBS Packages reference the time for observation values using KPER and KSTP. Special consideration of KPER and KSTP should be given when using values for **modflow\_time\_zero** that are not the same as **start\_time**.

*KPER* Global stress period number, where stress period 1 begins at **modflow\_time\_zero** and increments consecutively to the end of the simulation.

*KSTP* Time step number, where time step 1 begins at the start of each stress period and increments consecutively to the end of each stress period.

*TOTIM* Global model time, where TOTIM is zero at **modflow\_time\_zero** and increments consecutively to the end of the simulation.

*PERTIM* Elapsed time in current stress period, where time begins at the beginning of the current stress period and increments consecutively to the end of the current stress period.

## CONTROLLING SCREEN OUTPUT

There can be a large amount of information printed to the screen, including general information, warning messages, and error messages during initialization of a simulation. Sometimes this can make it difficult to see important error messages. There are several ways to reduce screen output. Set control parameter **parameter\_check\_flag** to 0 in the Control File to minimize warning messages about parameter values falling outside the suggested range. Set control parameter **print\_debug** to -2 (minimum output, including not producing the PRMS **model\_output\_file**) or -1 (less output). However, setting **parameter\_check\_flag** = 1 and **print\_debug** = 0 is good practice during initial model development as all warning and error messages are available. But, once warnings are deemed acceptable, **parameter\_check\_flag** should be set to 0 and **print\_debug** to -1 or -2.

## FLEXIBLE DIMENSIONS FOR PRMS PARAMETERS

There are several ways to specify parameters. Traditionally, a single value is specified per line. However, multiple values can be specified per line if fewer than 12,000 characters are specified and there are no trailing blanks. This might be useful to specify a parameter as a grid of values,

similar to MODFLOW input as columns by rows with the upper left value specified for column 1 row 1 and the bottom right value specified for last column and last row.

Previously, parameters had only one option for the number of values (dimension(s)) specified in the Parameter File. Now, most parameters can be specified using the maximum dimension(s) or using compatible dimensions, i.e., dimension(s) that are even multiples of the maximum dimension(s). This parameter specification capability is referred to as the flexible dimension option. For example, specifying a parameter with a maximum dimension of **nhru,nmonths** can be done using a single dimension: **one**, **nmonths**, **nsub**, or **nhru**, or double dimensions: **nsub,nmonths**, and **nhru,nmonths**. The dimension options for a parameter with a maximum dimension of **nhru** are **one**, **nsub**, and **nhru**. The dimension options for a parameter with a maximum dimension of **nssr** are **one**, **nsub**, and **nssr**. The dimension options for a parameter with a maximum dimension of **ngw** are **one**, **nsub**, and **ngw**. PRMS will read the dimension, number of values, and values from the Parameter File. If the parameter is not specified at the maximum dimension, values will be automatically expanded to the maximum dimension. For example, if a parameter has a maximum dimension of **nhru,nmonths** and it is specified with **nmonths** (12) values, then each HRU will be assigned the same monthly values. Thus, the user has several options to specify the number of parameter values based on the spatial and temporal variability, available data, or for some other purpose. Additionally, the number of lines in Parameter Files can be significantly reduced by specifying a single (dimension **one**) or **nsub** values for parameters that have a constant value for all HRUs or subbasins.

The maximum number of values for some parameters were changed with PRMS version 4.0.1. Increasing the maximum number of values accommodated the simulation of large model domains that required increased spatial and/or temporal distribution of parameter values. For example, some parameters having dimension of **nmonths** now have a maximum dimension of **nhru,nmonths** and some parameters having dimension of **nhru** now have a maximum dimension of **nhru,nmonths**.

Note, that using different numbers of values may change results when dimensions are specified greater than the original dimension(s) of older models while allowing for increased ability to calibrate spatially and temporally. Maximum parameter dimensions are identified in updated tables 1-1 and 1-3 in the file `PRMS_tables_5.2.0.pdf`.

## PRMS INITIAL CONDITIONS FILES

The PRMS Initial Conditions File is read whenever control parameter **init\_vars\_from\_file** is specified > 0. Various initial states can be updated for a restart simulation using initial value

parameters as specified in the PRMS Parameter File depending on the value of **init\_vars\_from\_file**:

0 = do not read Initial Conditions File and use all initial value parameters as read from PRMS Parameter File;

1 = read all initial value parameters;

2 = read **dprst\_frac\_init**, **snowpack\_init**, **segment\_flow\_init**, **elevlake\_init**, **gwstor\_init**, (**soil\_rechr\_init**, **soil\_moist\_init**, **ssstor\_init** for **model\_mode** = PRMS or GSFLOW) or (**soil\_rechr\_init\_frac**, **soil\_moist\_init\_frac**, **ssstor\_init\_frac** for **model\_mode** = PRMS5 or GSFLOW5), and **stream\_tave\_init**;

3 = read **snowpack\_init**;

4 = read **elevlake\_init**;

5 = read (**soil\_rechr\_init\_frac**, **soil\_moist\_init\_frac**, **ssstor\_init\_frac** for **model\_mode** = PRMS5 or GSFLOW5);

6 = read **gwstor\_init**;

7 = read **dprst\_frac\_init**;

8 = read **stream\_tave\_init**.

Options 2 and 3 could be used, for example, to update the snowpack in a restart simulation by specifying values for **snowpack\_init** to reflect an observed or model snow water equivalent data set. Option 8 could be used, for example, to update the stream temperature in each segment in a restart simulation by specifying values for **stream\_tave\_init** to reflect an observed or modeled stream temperature data set.

Options that cannot change for a restart simulation include: a) surface depression storage simulation option; b) cascading flow simulation option; c) dimensions **nhru**, **nssr**, **ngw**, **nsegment**, **nhrucell**, **nlake**; d) the model mode (GSFLOW, PRMS-only, or MODFLOW-only); and e) use of modules **temp\_1sta**, **temp\_laps**, **temp\_dist2**, **potet\_pan**, **transp\_tindex**.

Binary (unformatted) files used for initial conditions and restart simulations must be created by the same model executable that is used to run the simulation.

## MODEL MODES

The control parameter **model\_mode** is used to specify a variety of simulation and output options. If **model\_mode** is not specified, the default value is GSFLOW5. The available values of **model\_mode** are:

GSFLOW5, or PRMS5 – This mode uses the parameters **tmax\_allrain\_offset**, **soil\_rechr\_max\_frac**, **soil\_rechr\_init\_frac**, **soil\_moist\_init\_frac**, **ssstor\_init\_frac**, **sro\_to\_dprst\_perv**, and **dprst\_frac**

PRMS or PRMS4 – This mode uses the parameters **tmax\_allrain**, **soil\_rechr\_max**, **soil\_rechr\_init**, **soil\_moist\_init**, **ssstor\_init**, **sro\_to\_dprst**, and **dprst\_area**.

CONVERT – This mode computes and produces the file `PRMS_5.params` that contains parameters **tmax\_allrain\_offset**, **soil\_rechr\_max\_frac**, **soil\_rechr\_init\_frac**, **soil\_moist\_init\_frac**, **ssstor\_init\_frac**, **sro\_to\_dprst\_perv**, and **dprst\_frac** used in a PRMS5 simulation on the basis of an existing Parameter File used with a PRMS4 simulation. The deprecated PRMS4 parameters can be removed from the existing Parameter File.

CONVERT4 – This mode computes and produces the file `PRMS_4.params` that contains parameters **tmax\_allrain**, **soil\_rechr\_max**, **soil\_rechr\_init**, **soil\_moist\_init**, **ssstor\_init**, **sro\_to\_dprst**, and **dprst\_area** used in a PRMS4 simulation on the basis of an existing Parameter File used with a PRMS5 simulation. The PRMS5 parameters can be removed from the existing Parameter File.

FROST – This mode computes and writes the file `frost_date.param` of frost parameters (**spring\_frost** and **fall\_frost**) using the **frost\_date** module that can be used by the **transp\_frost** module in subsequent simulations. Simulation includes reading input (Data File, CBH File(s), Dynamic Parameter File(s), and Water-Use File(s)) and simulating temperature and precipitation processes. All other processes are not simulated. The `statvar`, `animation`, `nhru_summary`, `nsub_summary`, `nsegment_summary`, and `basin_summary` options can be used to output active variables.

WRITE\_CLIMATE – This mode computes and writes Climate-by-HRU (CBH) File(s) for all climate processes that have the module parameters **precip\_module**, **temp\_module**, **et\_module**, **swrad\_module**, and/or **transp\_module** specified as **climate\_hru**. The filenames for CBH Files are specified by the control parameter; these are: **precip\_day** (**precip\_module**); **tmax\_day** and **tmin\_day** (**temp\_module**); **potet\_day** (**et\_module**); **swrad\_day** (**swrad\_module**); and **transp\_day** (**transp\_module**). The generated CBH File(s) can be used by the **climate\_hru** module in subsequent simulations. In this mode, the code reads input files (Data File, CBH File(s), Dynamic Parameter File(s), and/or Water-Use File(s)) and simulates temperature, precipitation, solar radiation, transpiration, and potential evapotranspiration processes. Specified CBH files are then written. All other processes are not simulated.

CLIMATE – This mode simulates climate processes only. The simulation reads input files (Data File, CBH File(s), Dynamic Parameter File(s), and/or Water-Use File(s)) and simulates temperature and precipitation. All other processes are not simulated. The `statvar`, `animation`, `nhru_summary`, `nsub_summary`, `nsegment_summary`, and `basin_summary` options can be used to output active variables.

POTET – This mode simulates processes through potential evapotranspiration. The simulation reads input files (Data File, CBH File(s), Dynamic Parameter File(s), and/or Water-Use File(s)) and computes temperature, precipitation, solar radiation, transpiration, and potential evapotranspiration processes. All other processes are not simulated. The `statvar`, `animation`, `nhru_summary`, `nsub_summary`, `nsegment_summary`, and `basin_summary` options can be used to output active variables.

TRANSPIRE – This mode simulates processes through transpiration (active growing season). The simulation will only read input files (Data File, CBH File(s), Dynamic Parameter File(s), and Water-Use File(s)) and compute temperature, precipitation, solar radiation, and transpiration. All other processes are not simulated. The `statvar`, `animation`, `nhru_summary`, `nsub_summary`, `nsegment_summary`, and `basin_summary` options can be used to output active variables.

DOCUMENTATION – This mode generates a Parameter File (control file name plus suffix `.param`), a file of parameter definitions (control file name plus suffix `.par_name`), and a file of variable definitions (control file name plus suffix `.var_name`) as if all simulation options are active. The generated Parameter File contains all parameters, at their maximum dimension, that are needed for all modules and simulation options in the functionality list above. No hydrologic processes are simulated. The command line option `-print` must be specified. When the command line option `-print` is specified for any **model\_mode** other than `DOCUMENTATION` these files include parameters and variables for the active modules and simulation options as specified by values in the Control File. These `_name` files provide documentation of parameters and variables that can be used in lieu of the file `PRMS_tables_5.2.pdf` though in a less readable format. All parameters are expanded to their maximum dimension(s) and written to the `.param` file. If a parameter is included in the Parameter File(s) the values are written as specified. Parameters that are required by the set of modules that are not included in the Parameter File(s) are written with their default value(s). Parameters specified in the Parameter File(s) that are not required by the set of modules executed are not written to the `.param` file.

## CURRENT RELEASE

This version of GSFLOW (2.2.0) is based on MODFLOW-NWT version 1.2, MODFLOW-2005 version 1.12.0, and PRMS version 5.2.0. Significant modifications are described below, beginning with changes to PRMS and GSFLOW Modules and then changes to MODFLOW Packages.

- Initial Condition Files (i.e., Restart Files or antecedent conditions files) generated by previous versions of GSFLOW are not compatible with this version, thus they must be regenerated. Previous versions are not compatible because many basin area-weighted

variables from prior versions of Restart Files are not needed to restart a simulation and are no included in the Initial Conditions Files.

- New files are: `prms_constants.f90` (contains constant values that are used by many modules that are used to improve code readability and consistency of numerical constants; some constants are new and others moved from `call_modules.f90` and `basin.f90`); `glacr_melt.f90` (glacier dynamics module); and `precip_map.f90` and `temp_map.f90` (precipitation and temperature distribution modules, respectively, on the basis of mapping from input file to HRUs).
- Changed how module version dates and descriptions are printed to screen and increased consistency in module declarations.
- Water use information applied in associated PRMS process modules instead of in module `water_use_read`. For example, transfers to/from PRMS lakes are applied in `muskingum_lake` and transfers to/from surface depression storage are applied in `srunoff_smidx` and `srunoff_carea`. The transfers were already applied in `soilzone`, `intcp`, and `gwflow`.
- There have been numerous changes to the `stream_temp` module since the previous release to address bugs. This version of the module will give significantly different simulation results than previous versions. Any modeling work done with previous versions of this module should be redone with this (or subsequent) releases.
- The `gsflow.log` file is no longer written.

## PRMS and GSFLOW Modules and PRMS utilities

### BUG FIXES – by module:

#### `dynamic_parameter_read`

- Dynamic parameters **`soil_moist_max`**, **`soil_rechr_max`**, and **`soil_rechr_max_frac`** were ignored.

#### `muskingum` and `muskingum_mann`

- Restart File was incorrect as the string length of the module name was checked using a different string length.

#### `snowcomp`

- Fixed possibility of divide by zero when setting maximum snow-water equivalent value (variable *ai*) and computing the fraction of maximum snow-water equivalent (variable *frac\_swe*). The former can happen when the maximum snow-water equivalent threshold (parameter **`snarea_thresh`**) value is 0.0 on an HRU. The latter can occur when values of *ai* are small (<0.1). variable *ai*.
- Variable *ai* is reset when snowpack disappears instead of every timestep.
- Variable *ai* is saved in the Restart File.
- Variables *scrsv*, *pksv*, *pk\_den*, and *frac\_swe* are reset when snowpack disappears during a timestep.

#### `stream_temp`



- Improved calculations of stream temperatures from stream flow coming from upstream segments.
- Improved calculations of water temperatures from lateral flows from adjacent land surfaces (i.e. lateral components of flow from adjacent HRUs).
- Improved calculations of water temperature due to the daily energy fluxes on the stream segments.

mmf.c

- Removed an extra argument to three usages of routine `fprintf` that caused warning messages to be issued during compilation.

## NEW FUNCTIONALITY

prms\_constants.f90

- This file defines constants used by many PRMS Modules. These constants are named to increase readability of the FORTRAN code; they do not affect model input, such as specified in the Parameter and Control Files. For example, the constant `FAHRENHEIT` is set equal to 0 and `CELSIUS` is set equal to 1 to use in module code to check the value of parameter **temp\_units**, if the user specifies as 0 for Fahrenheit and 1 for Celsius in a Parameter File. Similarly, constants `SAND` is set equal to 1, `LOAM` = 2, and `CLAY` = 3 to use in modules that check the value of parameter **soil\_type**. Another example is the named constants `ON` and `OFF` that are set to 1 and 0, respectively. Some values were moved from other files, mostly from files `call_modules.f90` and `basin.f90`.

precip\_map

- This module distributes precipitation to each HRU using precipitation data specified in a Map File as a time series of gridded or other spatial units using an area-weighted method and a correction factor to account for differences in altitude, spatial variation, topography, and data accuracy between the spatial scale of the values specified in the Map File and HRUs. The module requires daily input, thus, any temporal discrepancies (i.e., the values in the Map File are valid for noon one day to noon of the second day are not considered. Values are assumed to be valid for each full day. The Map File is a text file with each day specified by a date and time (year, month, day, hour, minute, second) followed by **nhru** values in order of HRU 1 through **nhru**. Each value can be separated by a space and/or comma. The values for hour, minute and second are specified as 0. For example, the date and time of 2021/1/20 12:15:00:00 can be specified as: 2021 1 20 12 15 0 0 0. Any number of lines can be used to specify each day. For example, if the HRUs are a grid, one way to specify a day is the date on one line followed by values in a gridded format with the number of lines equal to the number of rows in the grid and the number of values on a line equal to the number of columns in the grid. Each HRU is associated with one or more values in the Map File as a fraction based on an intersection of the HRU map and gridded or other map. Use of this option can increase execution speed by reducing the volume of input read during a simulation for models that would require very large climate-by-HRU (CBH) Files that are typically pre-

processed distributions of gridded data. Typically, the source gridded data file is much smaller than a CBH File. Additionally, the module allows for calibration adjustments using parameters. See below and/or in the file `PRMS_tables_5.2.pdf` for a description of the required dimensions and parameters, each are labeled with `precip_map` (dimensions **nmap** and **nmap2hru**, parameters **hru2map\_id**, **hru2map\_pct**, **map2hru\_id**, and **precip\_map\_adj**)

#### `temp_map`

- This module distributes maximum and minimum temperatures to each HRU using precipitation data specified in a Map File as a time series of gridded or other spatial units using an area-weighted method and a correction factor to account for differences in altitude, spatial variation, topography, and data accuracy between the spatial scale of the values specified in the Map File and HRUs. The module requires daily input, thus, any temporal discrepancies (i.e., the values in the Map File are valid for noon one day to noon of the second day are not considered. Values are assumed to be valid for each full day. The Map File is a text file with each day specified by a date and time (year, month, day, hour, minute, second) followed by **nhru** values in order of HRU 1 through **nhru**. Each value can be separated by a space and/or comma. The values for hour, minute and second are specified as 0. For example, the date and time of 2021/1/20 12:15:00:00 can be specified as: 2021 1 20 12 15 0 0 0. Any number of lines can be used to specify each day. For example, if the HRUs are a grid, one way to specify a day is the date on one line followed by values in a gridded format with the number of lines equal to the number of rows in the grid and the number of values on a line equal to the number of columns in the grid. Each HRU is associated with one or more values in the Map File as a fraction based on an intersection of the HRU map and gridded or other map. Use of this option can increase execution speed by reducing the volume of input read during a simulation for models that would require very large climate-by-HRU (CBH) Files that are typically pre-processed distributions of gridded data. Typically, the source gridded data file is much smaller than a CBH File. See below and/or in the file `PRMS_tables_5.2.pdf` for a description of the required dimensions and parameters, each are labeled with `precip_map` (dimensions **nmap** and **nmap2hru**, parameters **hru2map\_id**, **hru2map\_pct**, **map2hru\_id**, and **temp\_map\_adj**)

#### `glacr_melt`

- This module computes glacier dynamics using three linear reservoirs (snow, firn, ice) with time lapses and ability to advance or retreat according to volume-area scaling. The altitude of HRUs can change due to glacial dynamics on any time step, so climate distribution methods that are based on lapse rates use the altitude computed on the previous time step of glacier HRUs. This affects modules `xyz_dist`, `temp_laps`, `precip_laps`, `temp_1sta`, `temp_dist2`, `ide_dist`, and `basin`. The addition of glacier dynamics required significant changes to the `snowcomp` module. New variables were added for glacier runoff to the stream network and from HRUs. An HRU that is or might become glaciated during a simulation is specified by setting the value of parameter **hru\_type** to 4.

## Frozen ground dynamics

- Code was added to the modules `basin`, `water_balance`, `srunoff_smidx`, `srunoff_carea`, and `soilzone` to include the continuous frozen ground index (CFG I) method. This addition did not require a new module.

## Irrigation application to the canopy – `intcp`

- A value for parameter **`irr_type`** is specified for each HRU that is used to select how irrigation water, as input to the `water_use_read` module, is applied within an HRU. The meaning of each **`irr_type`** value follows. Two options for **`irr_type`** have been added with this release. The first new option (**`irr_type=3`**, sprinkler application) applies the specified amount of water across the whole HRU, which allows the specified irrigation water to be applied to the plant canopy and non-covered areas, which allows for interception and throughfall across the HRU. The existing options, **`irr_type=0`** and **`irr_type=1`**, sprinkler and ditch/drip application, respectively, apply the specified irrigation water only to the canopy. For **`irr_type = 1, 2, or 3`** the irrigation water is specified as an HRU-area weighted average value. The second new option (**`irr_type=4`**, living filter application) allows for the irrigation water amount to be specified as the amount of water applied to the plant canopy, i.e., not an HRU-area average value. Note, **`irr_type=2`** signals to ignore any specified irrigation water.

## Stop conditions

- ERROR messages issued by modules have been reworded to be more consistent in format. Additionally, in ERROR messages and at the termination of a simulation a value is output. A non-zero value indicates an ERROR was detected in the simulation. The values are output according to the following list:
  - 4 = read input error
  - 3 = open output file error
  - 2 = open input file error
  - 1 = write output error
  - 0 = no error
  - 1 = control parameter error
  - 2 = variable range error
  - 3 = dimension range error
  - 4 = parameter range error
  - 5 = data file input error
  - 6 = timestep error
  - 7 = air temperature range error
  - 8 = streamflow range error
  - 9 = basin module error
  - 10 = Climate-by-HRU (CBH) input error
  - 11 = Cascade input error
  - 12 = Restart file error
  - 13 = Dynamic parameter error
  - 14 = Water-use error

- 15 = parameter or variable error
- 16 = module error
- 17 = lake error
- 18 = soilzone error

## NEW DIMENSIONS

**nmap** - Number of spatial units in mapped climate, used in modules `temp_map` and `precip_map`.

**nmap2hru** - Number of intersections between HRUs and spatial units in mapped climate, used in modules `temp_map` and `precip_map`

**four** – Number of glacier variables in integer array, fixed at 4, used in module `glacr_melt`.

**nglres** - Number of reservoirs in a glacier, fixed at 3, used in module `glacr_melt`.

**seven** - Number of glacier variables in real array, fixed at 7, used in module `glacr_melt`.

## PARAMETER CHANGES

### *New Parameters read from the Control File:*

#### **frozen\_flag**

- Flag to indicate if continuous frozen ground index simulation is computed (0=no; 1=yes)

#### **glacier\_flag**

- Flag to indicate if glacier simulation is computed (0=no; 1=yes)

#### **mbInit\_flag**

- Flag to indicate the method used for initial mass balance of glaciers (0=no optimization; 1=use first year of climate data; 2=constant mass balance gradient above and below equilibrium line altitude (ELA))

#### **stream\_temp\_shade\_flag**

- Flag to indicate how shade is used in the `stream_temp` module (0 = compute shade; 1 = specified as a constant)

#### **PRMS\_iteration\_flag**

- Previous versions only included the `soilzone` module in the MODFLOW iteration loop. This version allows the simulation of interception, snow dynamics, surface runoff, and depression storage simulation in addition to the soilzone processes to be included in the MODFLOW iteration loop. Including the additional processes in the iteration loop was done so that the MODFLOW Agriculture Package can apply irrigation to the canopy (0=only soilzone computations in the MODFLOW iteration loop; 1=interception, snow dynamics, surface runoff, depression storage, and soilzone processes are included in the MODFLOW iteration loop)

#### **outputSelectDatesON\_OFF**

- Switch to indicate if `nhru_summary` output files are generated for a specified set of dates (0=no, output time series on basis of `nhruOut_freq`; 1=yes, specify dates in file specified by **selectDatesFileName**)

**selectDatesFileName**

- String to define the filename of the set of dates to output values of `nhru_summary` output files in chronological order with dates specified as YEAR MONTH DAY with a space(s) and/or comma separating YEAR and MONTH and MONTH and DAY (e.g. 1959 09 01)

**New Parameters: read from Parameter Files**

See the file `PRMS_tables_5.2.0.pdf` for descriptions of the 16 new parameters related to the simulation of glacier dynamics. These are identified by highlighted **red** text in the Glacier and frozen ground computations section of Table 1-3.

**hru2map\_id** – used in modules `temp_map` and `precip_map`

- HRU identification number associated with each intersection between the HRU map and grid or other spatial unit map with **nmap2hru** number of values and maximum value **nhru**

**hru2map\_pct** – used in modules `temp_map` and `precip_map`

- Portion of HRU associated with each intersection between the HRU map and grid or other spatial unit map with **nmap2hru** number of values, expressed as a decimal fraction

**map2hru\_id** – used in modules `temp_map` and `precip_map`

- Grid or other spatial unit identification number associated with each intersection between the HRU map and grid or other spatial unit map with **nmap2hru** number of values with maximum value **nmap**

**precip\_map\_adj** – used in module `precip_map`

- Monthly (January to December) multiplicative adjustment factor to mapped precipitation to account for differences in elevation, and so forth

**tmax\_map\_adj** – used in module `temp_map`

- Monthly (January to December) additive adjustment factor to maximum air temperature for each mapped spatial unit estimated on the basis of slope and aspect

**tmin\_map\_adj** – used in module `temp_map`

- Monthly (January to December) additive adjustment factor to minimum air temperature for each mapped spatial unit estimated on the basis of slope and aspect

**cfgi\_decay** – used in frozen ground simulation option

- Continuous frozen ground index (CFG I) daily decay index, value of 1.0 is no decay

**cfgi\_thrshld** – used in frozen ground simulation option

- Continuous frozen ground index (CFG) threshold value indicating frozen soil

**Updated Parameters read from a Parameter File:**

**hru\_type**

- A value of 4 specifies that the HRU is or can be glaciated.

**adjust\_rain and adjust\_snow**

- The maximum suggested value was increased to 3.0. They are used in modules `xyz_dist` and `ide_dist`.

**rain\_adj**

- The maximum suggested value was increased to 10.0. It is used in module `precip_1sta`.

**ssr2gw\_rate**

- The units were corrected to be inches/day and the maximum suggested value increased to 999.0. See equation 59 in the GSFLOW documentation report (`tm6d1_GSFLOW.pdf` in the “doc” directory) for the formulation of computing gravity drainage with **ssr2gw\_rate**. The parameter **ssrmax\_coef** was replaced with the constant 1.0, with units of inches.

**width\_alpha**

- The units were corrected to be meters and the maximum suggested value increased to 1000.0 and the default value changed to 1.0. It is used in the `stream_temp` module.

**irr\_type**

- Added two options (3 and 4) for application method of irrigation water for each water-use plant canopy time-series. Values are specified for each HRU with one of the following: 0 = sprinkler method with interception only; 1=ditch/drip method with no interception; 2=ignore; 3=sprinkler across whole HRU with interception and throughfall; and 4=sprinkler method with amount of water applied on the basis of cover density, such as a living filter. Note, for options 1, 2, and 3 the irrigation water is specified as an HRU-area weighted average value as cubic feet per second.

**NEW VARIABLES**

See the file `PRMS_tables_5.2.0.pdf` for descriptions of the 72 new variables related to the glacier dynamics and 3 new variables for frozen ground computations. These are identified by highlighted red text in Glacier and frozen ground computations section of Table 1-5.

**gwflow**

- **lakein\_gwflow** – Groundwater flow received from cascading upslope GWRs for each Lake GWR in units of acre-inches.

**basin**

- **hru\_elev\_ts** – HRU elevation for timestep, which can change for glaciers.

## MODFLOW Packages

GSFLOW version 2.2.0 is based on MODFLOW-NWT version 1.2 and some additional changes made since this last release. MODFLOW-2005 source files used in MODFLOW-NWT were updated to reflect changes made for MODFLOW-2005 version 1.12.0. Since the last GSFLOW release (version 1.2.2), there has been one MODFLOW-NWT release (version 1.2). Changes made to MODFLOW-NWT and MODFLOW-2005 also are described in the release notes for those codes; users are encouraged to review those release notes in addition to the notes provided below.

Changed files: `gwf2sfr7_NWT.f`, `gwf2uzf1_NWT.f`, `gwf2lak7_NWT.f`, `gwf2ag1_NWT.f`, `Irestart.f`, `gwf2mnw27_NWT.f`, `NWT1_solver.f`, `NWT1_module.f`

### Multi-Node Well (MNW2) Package

- Checks were added to the code to ensure head in the well bore (Hb) is not set equal to the intake altitude (HLIM) if HLIM is greater than head in the aquifer. This stops an extraction well from becoming a recharge well when HLIM is at a high elevation relative to regional groundwater levels. Similarly, for injection wells, a check was added to ensure Hb is not set equal to HLIM if HLIM is less than the head in the aquifer.

### Newton-Raphson Solver (NWT) Package

- A variable used to track the number of outer iterations during a times step was moved from the NWT module to GSFMODFLOW module.

### Lake (LAK) Package

- A check was added to initialize state variables for transient simulations that are not using restart data for initial conditions. Previously, lake stage was not getting set to the value specified in the LAK input file if the model was starting after **modflow\_time\_zero**.

### Restart utility for MODFLOW

- A flag created in the LAK Package was added to the list of variables saved for the Lake Package for restart simulations.

### Streamflow Routing (SFR2) Package

- A bug was fixed to correct the output variable for net seepage from streams through the UZF Package net seepage output option to account for multiple stream reaches within a single model cell.

### Agriculture (AG) Package

- Two bugs were fixed in this package. The first bug resulted in an error in how the supplemental pumping was calculated for models that conjunctively use surface water and groundwater. The second bug fixes how results were output to the timeseries output files for diversions and supplemental pumping. Finally, for integrated GSFLOW

simulations actual ET included only ET in the PRMS soilzone. Actual ET calculated in the unsaturated and saturated zones beneath the soil zone are included in the calculation of actual ET for the crop.

### **Unsaturated-Zone Flow (UZF1) Package**

- The groundwater ET variable was added to the formulate routine to allow groundwater ET to be included in the crop water consumption in the Agricultural Water Use Package.

## **Previous Versions**

### **Version 2.1.0 (March 04, 2020)**

This version of GSFLOW (2.1.0) is based on MODFLOW-NWT version 1.2, MODFLOW-2005 version 1.12.0, and PRMS version 5.1.0. New functionality has been added: (a) the MODFLOW-AG Package is now available for GSFLOW and MODFLOW-only modes; (b) the PRMS implementation of the SNTMP model (module `stream_temp`) and Muskingum routing based on Manning's N (module `muskingum_mann`) are now available for PRMS-only mode; (c) PRMS output summary for HRU dimensioned variables optionally can be output in a gridded CSV format; and (d) optional new methods that allow soil-water evapotranspiration computations to closely follow the potential evapotranspiration rate for water demand applications for PRMS-only and GSFLOW simulation modes and replenishing the upper and lower zones of the capillary reservoir for GSFLOW simulation modes. See Niswonger (2020) and the AG Package input instructions (`Input_instructions_AG.pdf`) included in the 'doc' subdirectory of the GSFLOW release for documentation of the MODFLOW-AG Package. See Sanders and others (2017) for documentation on the PRMS stream temperature simulation option.

Corrected major bugs in the `dynamic_param_read` module, where the dynamic parameter time series files were sometimes not being read correctly and the potential evapotranspiration coefficients were being reset every timestep instead of only when a new set of dynamic parameters were available for a given timestep. Note, variable `wind_speed` when specified in the PRMS Data File must be specified in units of meters per second (not miles per hour) for use with module `potet_pm_sta`. Parameter Files for example problems were converted to use the new PRMS5 parameters instead of the equivalent PRMS4 parameters. For the Tahoe example problem, the single Parameter File was split into three files and some parameters were specified in a gridded format that matches the MODFLOW grid.

### **PRMS and GSFLOW Modules and PRMS utilities**

**BUG FIXES** – by module:



`dynamic_param_read` and `utils_prms.f90`

- Dynamic parameter files were not always read correctly. The code now verifies that a line beginning with `####` starts each new set of values.

`dynamic_param_read`

- Variables `soil_moist_tot`, `basin_soil_rechr`, and `basin_soil_moist` were not always set correctly; no other computations were affected. Note, these were computed correctly by the `soilzone` module, thus they were correct at the end of a timestep.
- The potential evapotranspiration coefficients were being reset every timestep instead of only when a new set of dynamic parameters were available for a given timestep.

`cascade`

- Fortran compiler error to pass a function argument to another routine. This was not an error in earlier versions of compilers used to build GSFLOW.

`climateflow`

- Variable `orad` was always initialized to 0.0 instead of being set by value in the Restart File, if used. This doesn't affect any other computations.

`srunoff`

- Variable `hru_imperv_stor` was always initialized to 0.0 instead of being set by value in the Restart File, if used. This omission might have affected some water balance computations for restart simulations.
- Water-use input was not added to variable `infil` if there was also cascading flow.
- A rare, small, water balance issue was found for the conditions that canopy storage exists in an HRU on the day that the transpiration period changes (i.e., a change of growing season) and there is a decrease in canopy density, there is snowmelt, and there is not a mixed precipitation event. The excess canopy storage was added for the computation of soil infiltration and surface runoff. If all these conditions happened, it is likely the water balance for that day and that HRU would be off by very small amount, such as less than 0.003 inches. The amount would depend on the canopy cover density differences and maximum storage capacity in the canopy. This will only happen when the difference between `covden_sum` and `covden_win` is positive, with canopy storage, and snow on the ground at the growing season end, which often people have set as October 1, the old default value for `transp_end` when using module `transp_tindex`. Similarly, it could happen if the difference between `covden_win` and `covden_sum` is positive under the same conditions.

`potet_pm_sta`

- Variable `wind_speed` as specified in the PRMS Data File must be specified in units of meters per second, not miles per hour as documentation previously stated in error. This is not a bug in the code, but, an error in the documentation.

## CHANGES THAT CAN AFFECT SIMULATION RESULTS

### soilzone

- Values of soil-water evapotranspiration (ET) are computed based on the potential evapotranspiration (PET) rate instead of the unsatisfied ET rate (PET rate less canopy, snowpack, impervious storage, and surface-depression storage ET) when control parameter **soilzone\_aet\_flag** is specified equal to 1. Additionally, a change was made to how the capillary reservoir is replenished by water in the gravity reservoir when the capillary reservoir is below the maximum water-holding capacity (**soil\_moist\_max**) for GSFLOW and GSFLOW5 simulation modes. The upper zone of the capillary reservoir previously was replenished based on the fraction of the upper zone water holding capacity of **soil\_moist\_max** (**soil\_rechr\_max/soil\_moist\_max** for GSFLOW or **soil\_rechr\_max\_frac** for GSFLOW5). This method can lead to the upper zone not being saturated when the capillary reservoir is saturated, that is  $soil\_rechr/soil\_rechr\_max$  is less than 1 when  $soil\_moist/soil\_moist\_max$  equals 1. When **soilzone\_aet\_flag** is specified equal to 1 the lower zone of the capillary reservoir is replenished first, after this reservoir is full, additional water is added to the upper zone. This change ensures that the upper zone is saturated when the capillary reservoir is saturated and can produce increased soil zone ET since the upper zone, where soil-water evaporation and plant transpiration is computed, could have an increased overall water content than the previous method, especially when MODFLOW is generating groundwater discharge into the soil zone. These changes may significantly alter results of existing models compared to using previous versions of GSFLOW. The changes typically would increase soil-water ET and reduce soilzone storage, recharge rate, and unsaturated-zone and saturated zone storage and fluxes. If **soilzone\_aet\_flag** is not specified equal to 1, then soil-water ET and capillary replenishment in GSFLOW or GSFLOW5 modes is computed as done in previous versions, i.e., based on the unsatisfied PET rate and fraction of the upper zone of the total capillary reservoir water-hold capacity, thus maintaining downward compatibility for existing models. It is recommended that **soilzone\_aet\_flag** be specified equal to 1 for new models.
- If any lake evaporates at greater than the computed PET rate, then the PET rate is set equal to the lake evaporation rate for the lake HRU and variable *basin\_potet* is recomputed. This can occur if **lake\_evap\_adj** is specified greater than 1.0.

### utils\_prms.f90

- Open statements for PRMS binary files must specify UNFORMATTED instead of BINARY for Linux-based computers. This is a code difference between Windows and Unix versions. A second version of *utils\_prms.f90*, named *utils\_prms\_linux.f90* is provided for use on Linux-based computers.

## NEW FUNCTIONALITY

### muskingum\_mann

- Specifying control parameter **strmflow\_module** to `muskingum_mann` provides an additional method to compute **K\_coef** values, which are used along with values of parameter **x\_coef** to compute coefficients for the Muskingum streamflow routing method. Values of **K\_coef** are computed in routing.f90 based on the values of new parameters **mann\_n**, **seg\_length**, **seg\_depth**, and **seg\_slope**.
- $velocity = (1.0 \div \mathbf{mann\_n}(i)) \times \sqrt{\mathbf{seg\_slope}(i) \times \mathbf{seg\_depth}(i)^{2/3}}$
- $\mathbf{K\_coef}(i) = \mathbf{seg\_length}(i) \div (velocity \times 60 \times 60)$
- **K\_coef** values computed greater than 24.0 are set to 24.0, values computed less than 0.01 are set to 0.01, and the value for lake HRUs is set to 24.0. Note, **K\_coef** values are specified as a parameter when **strmflow\_module** is specified as `muskingum`
- 

### gsflow\_prms

- Added code related to use of MODFLOW irrigation MODFLOW-AG Package is active and modules `stream_temp` and `muskingum_mann`.

### gsflow\_modflow

- Added code related to use the MODFLOW-AG Package.

### gsflow\_mf2prms

- Add irrigation and stream segment diversion volumes (variable `hru_ag_irr`) to the soilzone of each HRU as determined by the MODFLOW-AG Package.

### snowcomp

- Snow depletion curves optionally can be specified using an equation on the basis of new parameters **snarea\_a**, **snarea\_b**, **snarea\_c**, and **snarea\_d** when control parameter **snarea\_curve\_flag** is specified equal to 1. Otherwise the snow depletion curves are specified as in previous versions using parameters **hru\_deplerv** and **snarea\_curve**. Each of 11 values of the depletion curve are computed as for each HRU (index *i*):

$$snarea\_curve(j, i) = (snarea\_a(i) - snarea\_d(i)) \div \left( 1 + \left( x^{snarea\_b(i)} \div snarea\_c(i) \right) \right) + snarea\_d(i)$$

where variable *x* equals 0.0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, and 1.0 as index *j* increments from 1 to 11. Note, **snarea\_a** is the minimum value of snowpack water equivalent (SWE) and defaults to 0 and values can have a maximum value of 1.0.

### nhru\_summary

- output summary optionally can be output in a gridded CSV format with number of columns of values specified by control parameter **nhruOutNcol**. If **nhruOutNcol** is specified equal to 0 or not specified each output line contains all **nhru** values as in previous versions.

### strmflow\_in\_out

- Parameter **segment\_flow\_init** applied in routing.f90 to allow initialization of flows in all segments instead of always starting with zero flows, code changes made in muskingum, muskingum\_lake, muskingum\_mann, and routing.f90.

#### dynamic\_param\_read

- Control parameter **dynamic\_param\_log\_file** added to allow the name of the log file to be specified rather than hard-coded. This allows multiple simulations to be executed in a single Windows directory as multiple log files can be open when different names are specified in each Control File.

## PARAMETER CHANGES

### *New Control Parameters:*

#### **dynamic\_param\_log\_file**

- Specifies the name of the log file written when the `dynamic_param_read` module is active.

#### **nhruOutNcol**

- Specifies the number of columns written per line for `nhru_summary` output, which can be used to generate gridded output. If not specified or set to 0, all values for each timestep are written on a single line as in previous versions.

#### **stream\_temp\_flag**

- Flag to activate simulation of stream temperature using the `stream_temp` module (0=off; 1=on).

#### **strmtemp\_humidity\_flag**

- Flag to specify where humidity information is read for use by the `stream_temp` module (0=CBH File specified by control parameter **humidity\_day**; 1=parameter **seg\_humidity**; 2=Data File with values assigned based on parameter **seg\_humidity\_sta**).

#### **soilzone\_aet\_flag**

- Flag to specify whether to compute soil-water evapotranspiration (ET) based on unsatisfied potential ET (PET) and for GSFLOW or GSFLOW5 modes replenish the upper zone of capillary reservoir using the fraction of the upper zone of the capillary reservoir as was done in previous versions) or based on PET when specified equal to 1 and replenish by first filling the lower zone and then the upper zone to their maximum water-holding capacities (0=compute soil-water ET based on unsatisfied ET and old upper zone replenishment method; 1=based on PET and new replenishment method); set to 0 for downward compatibility of old models though it is recommended setting to 1 for new models.

#### **snarea\_curve\_flag**

- Flag to specify whether to compute snow depletion curves for each HRU using an equation on the basis of new parameters **snarea\_a**, **snarea\_b**, **snarea\_c**, and **snarea\_d** when control parameter **snarea\_curve\_flag** is specified equal to 1. (0=specify snow depletion curves using parameters **hru\_deplcrv** and **snarea\_curve**; 1=compute snow depletion curves).

*Updated Control Parameters:*

#### **csvON\_OFF**

- If specified equal to 2, only simulated and measured streamflow pairs are written to PRMS CSV File specified by control parameter **csv\_output\_file**.

#### **print\_debug**

- If specified equal to -2, screen output is very limited and the PRMS water budget file specified by control parameter **model\_output\_file** is not generated and the **basin\_sum** module is not used. Thus, all computed variables unique to **basin\_sum** are not available. Additionally, the **gsflow.log** file is not written.

#### **strmflow\_module**

- New option: **muskingum\_mann**, where Muskingum routing parameter **K\_coef** is computed as described above.

*Updated Parameters:*

#### **lake\_evap\_adj**

- Maximum value changed to 1.5 to allow lakes to evaporate at greater than potential evapotranspiration (PET) rate, such as during winter months when lake water temperature may be greater than air temperature.

#### **den\_init, den\_max, settle\_const**

- These snow parameters now have a maximum dimension of **nhru**. Previously, they were scalar values (dimension of **one**).

*New Parameters:*

See the file 'PRMS\_tables\_5.1.0.pdf' for descriptions of the 27 new parameters related to the stream temperature module. These are identified by highlighted pink text in the Stream temperature simulation section of Table 1-3.

**ppt\_zero\_thresh** – changes in **climateflow**, **climate\_hru**, and **obs**.

- Sets the minimum value for precipitation values specified in the PRMS Data File specified by control parameter **data\_file** or CBH File specified by control parameter **precip\_day**. Precipitation values below this threshold are set to 0.0. Default value is 0.0. An example use case of this functionality is to control for drizzle associated with some downscaled general circulation model climate inputs.

**mann\_n** – added to **routing.f90**.

- Specifies the Manning’s roughness coefficient for each segment as a dimensionless value for use by module `muskingum_mann`. Default value is 0.04.

**seg\_slope** – added to `routing.f90`.

- Specifies the surface slope of each segment as approximation for bed slope as a decimal fraction for use by module `muskingum_mann`. Default value is 0.0001.

**seg\_length** – added to `routing.f90`.

- Specifies the length of each segment in meters for use by module `muskingum_mann`. Default value is 1.0.

**seg\_depth** – added to `routing.f90`.

- Specifies the segment depth at bank full of each segment in meters for use by module `muskingum_mann`. Default value is 1.0.

## NEW VARIABLES

See the file ‘PRMS\_tables\_5.1.0.pdf’ for descriptions of the 13 new variables related to the stream temperature module. These are identified by highlighted pink text in Stream temperature simulation section of Table 1-5.

`gsflow_prms`

- *hru\_ag\_irr* – irrigation added to PRMS soil zone from MODFLOW wells and stream segment diversions, computed in `gsflow_mf2prms` and used in `soilzone` module.

`soilzone`

- *soil\_saturated* – set to 1 if capillary zone is saturated by an infiltration event, otherwise set to 0.

## SMALL CHANGES THAT DO NOT AFFECT ANY COMPUTATIONS

`gsflow_prms`, `gsflow_modflow`, `gsflow_sum`, `gsflow_prms2mf`, and `utils_prms.f90`

- The `gsflow.log` file is not written when control parameter **print\_debug** is specified as -2.

`gsflow_budget`

- Removed eight unused local variables.

`gsflow_sum`

- Removed extra initialization of variable *Lake2Sat\_Q*. Add variables *Rate\_lakein*, *Rate\_lakot*, *Rate\_lakestor*, and *Rate\_dprst\_S* to the Restart File.

`muskingum`, `muskingum_lake`, and `routing.f90`

- Parameter **segment\_flow\_init** applied in `routing.f90` and so code is not duplicated in Muskingum modules.

climateflow

- Add variables *basin\_potsw* and *basin\_humidity* to the Restart File.

## **MODFLOW Packages**

GSFLOW version 2.2.0 is based on MODFLOW-NWT version 1.2 and some additional changes made since this last release. MODFLOW-2005 source files used in MODFLOW-NWT were updated to reflect changes made for MODFLOW-2005 version 1.12.0. Since the last GSFLOW release (version 1.2.2), there has been one MODFLOW-NWT releases (version 1.2). Changes made to MODFLOW-NWT and MODFLOW-2005 also are described in the release notes for those codes; users are encouraged to review those release notes in addition to the notes provided below.

Changed files: gwf2wel7\_NWT.f, gwf2bas7\_NWT.f , gwf2sfr7\_NWT.f , utl7.f , parutl7.f, gwf2uzf1\_NWT.f, obs2bas7.f, gwf2sfr7\_NWT.f, gwf2swt7.f, obs2bas7.f, gwfuzfmodule\_NWT.f, gwf2lak7\_NWT.f

Added files: gwf2ag1\_NWT.f

### **Streamflow Routing (SFR2) Package**

- A check was added to allow stream reaches to have altitudes below the cell bottom if streambed K (UHC) is zero.
- Capability was added to allow a single tabfile to specify flows into multiple stream reaches.

### **Well (WEL) package**

- Small changes to format statements

### **Unsaturated-Zone Flow (UZF1) Package**

- A new option was added to simulate root uptake from the unsaturated zone.

This option simulates root water uptake using a capillary gradient between a user specified root pressure and the simulated capillary pressure in the root zone. This optional approach relies on additional input values that are described in the file called

'Updated\_UZF\_input\_instructions\_NWT.pdf' located in the 'doc' subdirectory of the GSFLOW release. This formulation is documented in Lappala and others (1987) and Niswonger, 2020.

### **Lake (LAK) Package**

- The dead pool storage for a lake (volume of water below lowest outflow reach) is calculated and printed to the main listing file.

### **Basic (BAS) Package**

- Small changes were made to format statements.

### **Link-MT3DMS (LMT) Package**

- Bug fix to prevent specification of linker file in both the name file and the LMT input file. This was creating a potential for conflicting unit numbers
- Bug fix in LMT that was wrongly listing the first reach of IUPSEG as the 'from' node when it should have been using the last reach of the IUPSEG as the node from which flow is diverted to the diversion segment.
- Bug fix for writing cross-sectional area to linker file for MT3D-USGS. Previously, when a diversion diverts all flow, the code was using the wrong variable for flow for calculating stream cross-sectional area.

### **MODFLOW Utility (UTL, PARUTL) Packages**

- Small changes to format statements accommodate writing numbers with more digits.

### **References**

Lappala, E. G., Healy, R. W., & Weeks, E. P. (1987). Documentation of computer program VS2D to solve the equations of fluid flow in variably saturated porous media. Water-Resour. Invest. Rep, 83, 4099.

### **Version 2.0.0 (May 30, 2018)**

This version is based on MODFLOW-NWT version 1.1.4, MODFLOW-2005 version 1.12.0, and PRMS version 5.0.0. Unlike previous versions of GSFLOW, all MODFLOW-NWT Packages and PRMS Modules are included to provide support of all MODFLOW-only and PRMS-only simulations. Modifications that are more than simply code formatting are described below, beginning with changes to PRMS and GSFLOW Modules and then changes to MODFLOW Packages. Parameter Files for example problems were converted to use the new PRMS5 parameters instead of the equivalent PRMS4 parameters. For the Tahoe example problem, the single Parameter File was split into three files and some parameters were specified in a gridded format that matches the MODFLOW grid.

### **PRMS and GSFLOW Modules and PRMS utilities**

- This major release adds new functionality for input of dynamic parameters and water use data;
- Muskingum streamflow routing with simulation of lakes;
- output of subbasin, stream segment, and basin variables to Comma-Separated-Variable (CSV) files by activating modules `nsub_summary`, `nsegment_summary`, and/or `basin_summary`;
- an option to compute potential evapotranspiration by using the Penman-Monteith formulation on the basis of specified windspeed and humidity data in the Data File; and
- distribution of air temperature on the basis of specified minimum and maximum data in the Data File.

Also, corrected major bugs in the `potet_pm` and `potet_pt` modules and minor bugs in the `soilzone` and `gwflow` modules. PRMS Restart Files generated by previous versions of



GSFLOW are not compatible with the current version, thus they must be regenerated. The simulation time period for the antecedent simulation is written into the file and printed after it is read.

Several PRMS parameters are deprecated and replaced by new parameters that were added to facilitate automated model calibration. Most of the deprecated parameters were codependent with other parameters and were specified as a depth per unit area. The new parameters are specified as a fraction of, or offset to the related deprecated parameter. To use the new parameters, specify `model_mode` as PRMS5 for PRMS-only mode and GSFLOW5 for coupled mode. To retain downward compatibility, to use the deprecated parameters, specify `model_mode` as PRMS. Parameter Files for example problems were converted to use the new PRMS5 parameters instead of the equivalent PRMS4 parameters for PRMS-only mode and GSFLOW for coupled mode. A new module was added to facilitate adding the new parameters to an existing model. To activate this module, specify control parameter `model_mode` as CONVERT to produce a file of the new parameters. Similarly, specifying `model_mode` as CONVERT4 will produce a file of the old parameters based on a model using the new parameters. Once the new parameters are added to a Parameter File it is recommended the old parameters be removed.

See the file 'tm6b8\_PRMS\_enhancements.pdf' (Regan and LaFontaine, 2017) in the 'doc' subdirectory for documentation on the dynamic parameters; water-use, lake simulation, and HRU summary options.

See "Update of PRMS PET modules.pdf" file in the "doc\Related reports" subdirectory for corrections to PRMS-IV documentation report regarding the potential evapotranspiration modules. Screen and Model Output File output updated for readability and output of additional information.

## INITIAL CONDITIONS FILES

- Initial Condition Files made with previous PRMS versions are not compatible with this version; thus, they must be regenerated. The simulation time period for the antecedent simulation is written into the file and printed when used. The new files are about 75 percent smaller as only variables needed to maintain a water balance are stored. Modules with fewer values saved are: `gsflow_budget`, `snowcomp`, `soilzone`, `srunoff_smidx`, `srunoff_carea`, `routing`, `gwflow`, `intcp`, and `muskingum`.
- Restriction for changing to or from modules `potet_pt`, `potet_pm`, `potet_pm_sta`, `ide_dist`, and `xyz_dist` for restart simulations has been removed.
- Restriction for changing the content of Data File(s) for restart simulations has been removed.

- Options that cannot change for a restart simulation include: a) surface depression storage simulation option; b) cascading flow simulation option; c) dimensions **nhru**, **nssr**, **ngw**, **nsegment**, **nhrucell**, **nlake**; and d) the model mode (GSFLOW, PRMS-only, or MODFLOW-only); and e) use of modules `temp_1sta`, `temp_laps`, `temp_dist2`, `potet_pan`, `transp_tindex`.
- Various states can be updated for a restart simulation by using new options as specified by control parameter `init_vars_from_file` (0 = do not read initial value parameters; 1 = read all initial value parameters; 2 = read **dprst\_frac\_init**, **snowpack\_init**, **segment\_flow\_init**, **elevlake\_init**, **gwstor\_init**, (**soil\_rechr\_init**, **soil\_moist\_init**, **ssstor\_init** for **model\_mode** = PRMS or GSFLOW) or (**soil\_rechr\_init\_frac**, **soil\_moist\_init\_frac**, **ssstor\_init\_frac** for **model\_mode** = PRMS5 or GSFLOW5); 3 = read **snowpack\_init**; 4 = read **elevlake\_init**; 5 = read (**soil\_rechr\_init\_frac**, **soil\_moist\_init\_frac**, **ssstor\_init\_frac** for **model\_mode** = PRMS5 or GSFLOW5); 6 = read **gwstor\_init**; 7 = read **dprst\_frac\_init**). Options 2 and 3 could be used, for example, to update the snowpack based on observed values of snowpack water equivalent by restarting a simulation and specifying values for `snowpack_init` to reflect an observed or model snow water equivalent data set.

#### BUG FIXES – by module:

##### snowcomp

- When a snowpack is melting and there is a new snowfall, the code saves the point on the depletion curve (variable `snowcov_areasv`) and then depletes the snowpack from **snarea\_curve(11,k)** over the subsequent time steps until the snow cover is less than or equal to `snowcov_areasv` on the basis of linear interpolation. See Figure 1-4, page 97 of the PRMS-IV documentation report (TM6-B7, Markstrom and others, 2015) for a depiction of how to compute snow-water equivalent (SWE) using a depletion curve after a secondary snowfall. However, `snowcov_areasv` was set to **snarea\_curve(11,k)**, the maximum value of a snow depletion curve, instead of current value of `snowcov_area`. This issue was fixed. This change can affect results of the snowpack depletion for secondary snowfalls as depletion begins at the maximum value of the depletion curve instead of returning to the point of departure from the depletion curve from which it was melting prior to the snowfall. Thus, there will be no change for many simulations, but, noticeable changes could occur for some simulations.
- Variable `frac_swe` was not computed for all time steps, this was corrected, and the variables were changed to single precision; this change did not affect other computations.

- Variable *tcal* was not reset to 0.0 for all time steps, which might have meant values were carried over after a snowpack melted, this was corrected; this change did not affect other computations.
- Initial snow cover area was computed incorrectly, this would only affect the first timestep.

temp\_dist2

- Values for parameter **tmax\_adj** and **tmin\_adj** were not read from the Parameter File and were likely set to zero or very small values.

climate\_hru

- Corrected check that looked for first simulation time step in CBH Files that failed if simulation start month and year were earlier than the first date in the CBH File.

soilzone

- Parameters **soil\_moist\_max**, **soil\_rechr\_max**, and **soil\_rechr\_max\_frac** could have values specified equal to 0, which would cause divide by zero in several equations. To prevent divide by zeros and to allow for some minimum storage in capillary reservoirs to receive cascading flow, the code was modified to issue an error if values for these parameters are specified less than 0.00001. If control parameter **parameter\_check\_flag** is specified equal to 0, a warning message is issued, and the value is set to 0.00001.
- Parameters **slowcoef\_lin**, **slowcoef\_sq**, **fastcoef\_lin**, and **fastcoef\_sq** can have values specified equal to 0. However, under rare conditions, doing so could cause a divide by zero. The code was modified to trap for possible divide by zero and ensure a valid value is computed for interflow. Also, for some combinations of these parameters and a large gravity storage value it was possible to compute very small negative values of interflow due to floating point precision round off error. The code was modified to set any computed negative values of interflow to 0.

prms\_summary

- If values for optional parameter **poi\_gage\_segment** were greater than 999999 values in the header row were truncated at 7 digits. This has been corrected. Additionally, the format of the output values was changed from a fixed 10-digit exponential to values with 4 decimal places with as many values to the left of the decimal places as required.

gsflow\_modflow

- Restart didn't output stress period number correctly or skip through MODFLOW stress periods to simulation start time and didn't correctly read through observation files.

gsflow\_sum

- GSFLOW models that use seconds for time units in MODFLOW were incorrectly converting saturated storage change rates to volumes in the GSFLOW overall model budget tables.

gsflow\_budget

- GSFLOW models that use seconds for time units in MODFLOW were incorrectly calculating saturated zone storage.

routing.f90

- Values for solar radiation and potential evapotranspiration could be computed incorrectly for segments that did not have associated HRUs, this has been fixed to assign values from closest upstream segment.

## CHANGES THAT CAN AFFECT SIMULATION RESULTS

snowcomp

- For calculations of emissivity and energy related to convection or condensation, the code checks if there is precipitation on an HRU instead of anywhere in the model domain to adjust these values based on precipitation and cloud cover.
- Snow depletion curves must be specified, previous versions allowed snow depletion curves to not be specified when dimension **ndepl** was specified equal to 0.
- Several checks for small negative round-off errors were removed to reduce bias in round-off error. Thus, it is possible for some variables to have very small negative values. This should be a rare occurrence.

soilzone

- Values of **ssr2gw\_rate** specified less than 0.000001 were treated as 0. Now, all **ssr2gw\_rate** values > 0.0 are used to compute gravity drainage. In general, specifying parameter values < 0.000001 are going to produce results within or below the limits of floating-point precision, so they will be adding more noise and increased execution time than useful results.

intcp

- Previously, if there was canopy storage at the changeover of a transpiration period (winter to summer or summer to winter) and the canopy could not hold the antecedent water content, this water was added to *net\_rain*. This water is now kept track of in variables *intcp\_changeover* and *basin\_changeover* and added in the same manner as *net\_rain* in the `srunoff` module. Overall results don't change, except that *net\_rain* is consistent with the total amount of precipitation.

## NEW FUNCTIONALITY

dynamic\_param\_read

- Read and makes available dynamic parameters by HRU from pre-processed files.
- 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.

#### water\_use\_read

- Read and makes available water-use data (diversions and gains) from pre-processed files.
- 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 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.
- Modules `intcp`, `soilzone`, `srunoff_smidx`, `srunoff_carea`, `gwflow`, `strmflow_in_out`, `muskingum`, and `muskingum_lake` were modified to account for water-use transfers.

#### potet\_pm\_sta

- Computes the potential evapotranspiration by using the Penman-Monteith formulation (Penman, 1948; Monteith, 1965) using specified windspeed and humidity in the Data File.

#### muskingum\_lake

- Routes water between segments in the system using Muskingum routing and on-channel water body storage and flow routing.

#### temp\_sta

- Similar temperature distribution to `temp_1sta` except that no adjustment is made using lapse rates. The value of the associated temperature from a station by parameter `hru_tsta` is adjusted using parameters `tmax_adj` and `tmin_adj`.

#### nhru\_summary

- Added output yearly total and mean yearly time series on the basis of control parameter `nhruout_freq` (1 = daily, 2 = monthly, 3 = both, 4 = mean monthly, 5 = mean yearly, 6 = yearly total); daily files have the suffix `.csv`; monthly files have the suffix `_monthly.csv`; mean monthly have the suffix `_meanmonthly.csv`; and mean yearly and yearly total have the suffix `_yearly.csv`.
- Added the option to output of NHM HRU identification number (parameter `nhm_id`) to CSV files when control parameter `nhruOutON_OFF` is specified equal to 2.
- Added the capability to output integer variables in addition to real and double variables.
- Added the option to output using different formats using new control parameter `nhruOut_format` (1 = scientific notation with 4 significant digits (default); 2 = 2 decimal places; 3 = 3 decimal places; 4 = 4 decimal places; 5 = 5 decimal places).
- Parameter `prms_warmup` is now specified in the Control File.

#### nsub\_summary

- Summary output module that operates similar to `nhru_summary` and with similar control parameters, except that it is used to write values of variables dimensioned with **nsub** and variables dimensioned with the value of **nhru** when parameter **hru\_subbasin** is specified to separate CSV files at daily, monthly, mean monthly, mean yearly, and yearly total time steps when control parameter **nsubOutON\_OFF** is specified equal to 1.
- Added the capability to output integer variables in addition to real and double variables.
- Added the new control parameter **nsubOut\_format** for outputting different number formats (1 = scientific notation with 4 significant digits (default); 2 = 2 decimal places; 3 = 3 decimal places; 4 = 4 decimal places; 5 = 5 decimal places).

#### `nsegment_summary`

- New summary output module that operates similarly to `nhru_summary` and with similar control parameters except that it is used to write values of variables dimensioned with **nsegment** to separate CSV files at daily, monthly, mean monthly, mean yearly, and yearly total time steps when control parameter **nsegmentOutON\_OFF** is specified equal to 1.
- Added the new control parameter **nsegmentOut\_format** for outputting different number formats (1 = scientific notation with 4 significant digits (default); 2 = 2 decimal places; 3 = 3 decimal places; 4 = 4 decimal places; 5 = 5 decimal places).

#### `basin_summary`

- New summary output module that operates like `nhru_summary`, with similar control parameters, except that it is used to write values of variables dimensioned with **one** to separate CSV Files at daily, monthly, mean monthly, mean yearly, and yearly total time steps when control parameter **basinOutON\_OFF** is specified equal to 1.

#### `map_results`

- Parameter **prms\_warmup** is now specified in the Control File.

#### `potet_pt`, `potet_pm`, and `potet_pm_sta`

- Allows humidity data to be specified using new parameter **humidity\_percent** that has maximum dimensions **nhru** by **nmonths** as an alternative to specifying humidity in a CBH file. Note, previous versions of the `potet_pt` module did not require humidity data.

#### `cascade`

- Parameter **hru\_segment** can now be used to specify simple one-to-one HRU to stream segment cascade paths instead of specifying all cascade parameters with **cascade\_flag** set equal to 2. This option assumes **ncascade = ncascdgw = nhru** and indicates that parameters **hru\_up\_id**, **hru\_strmseg\_down\_id**, **hru\_down\_id**, **hru\_pct\_up**, **gw\_up\_id**, **gw\_strmseg\_down\_id**, **gw\_down\_id**, **gw\_pct\_up**, **cascade\_tol**, **cascade\_flg**, and **circle\_switch** are not specified.

#### `prms_summary`

- Produces an output file of daily values of select basin area-weighted variables to a comma-separated values (CSV) file when control parameter **csvON\_OFF** is specified equal to 1. The name of the output file is specified by control parameter **csv\_output\_file**. See Regan and LaFontaine (2017) for a description of the variables output.

#### convert\_params

- Produces an output file of replacement parameters added to facilitate calibration efforts. To activate this module, specify control parameter **model\_mode** as CONVERT to produce a file of the new parameters (**tmax\_allrain\_offset**, **soil\_rechr\_max\_frac**, **soil\_rechr\_init\_frac**, **soil\_moist\_init\_frac**, and **ssstor\_init\_frac**). Similarly, specifying **model\_mode** as CONVERT4 will produce a file of the old parameters (**tmax\_allrain**, **soil\_rechr\_max**, **soil\_rechr\_init**, **soil\_moist\_init**, and **ssstor\_init**) based on a model using the new parameters.

#### gsflow\_modflow

- Allow for stopping non-convergent simulation in MODFLOW-only mode for ICNMGFLG=0 for simulations with NWT and BUDPERC>STOPER for other solvers.

#### Temperature modules

- To make a consistent check for valid temperature ranges the constants MAXTEMP (value = 200.0) and MINTEMP (value = -150) were added to `basin`. Distributed values are compared to these values to determine if they are “valid”. Values outside this range are treated as missing values. Previously, some modules used the range 150.0 to -99.0.

### MODULE REMOVED

#### strmflow\_lake

- This module (files `strmflow_lake.f90` and `lake_route.f90`) was replaced by the `muskingum_lake` module with all functionality retained in the new module, which includes routing of streamflow using the Muskingum method.

### PARAMETER CHANGES

Notes: there are several ways to specify parameters. Traditionally, a single value is specified per line. However, multiple values can be specified per line if fewer than 12,000 characters are specified and there are no trailing blanks. This might be useful to specify a parameter as a grid of values as **ncol,nrow** with the upper left value specified for column 1 row 1 and the bottom right value specified for column **ncol**, row **nrow**. See the section of flexible dimension option described below under release version 4.0.1 for a simplified method of specifying parameters with constant values for any dimension of a parameter.

#### print\_debug

- If specified equal to -2, screen output is very limited and the PRMS water budget file specified by control parameter **model\_output\_file** is not generated and the

`basin_sum` module is not used. Thus, all computed variables unique to `basin_sum` are not available.

#### **prms\_warmup**

- This parameter is now a Control Parameter to allow it to be changed more easily. If specified in the Parameter File, it is ignored. This parameter is used in `nhru_summary`, `map_results`, `nsub_summary`, `nsegment_summary`, and `basin_summary` to designate a portion of a simulation to not include in the output file(s) for these modules..

#### **gw\_seep\_coef**

- The dimension is now **ngw** instead of **nlake**

#### **humidity\_percent**

- This new parameter can be used as an alternative to specification of humidity in a CBH file for modules `potet_pt`, `potet_pm`, and `potet_pm_sta`. It has maximum dimensions **nhru** by **nmonths**.

#### **obsout\_segment**

- This new parameter is used to specify a replacement flow for outflow of a segment. This is like **obsin\_segment** that can be used to specify a replacement flow for the inflow to a segment. Both parameters can be used with modules `strmflow_in_out`, `muskingum`, and `muskingum_lake`, which are available in PRMS or PRMS5 simulation modes. Replacement flows are specified in the Data File and used to assign measured flows to segments instead of the simulated flow. Use of replacement flows breaks conservation of mass, but, might be useful to set flows below a managed water body.

#### **segment\_type**

- Specifies type of segment (0 = normal; 1 = headwater; 2 = lake; 3 = replacement flow; 4 = inbound to nation; 5 = outbound from nation; 6 = inbound to region; 7 = outbound from region; 8 = drains to ocean; 9 = sink (terminus to soil); 10 = inbound from Great Lakes; 11 = outbound to Great Lakes; 12 = ephemeral; + 100 user updated; 1000 user virtual segment 100 = user normal; 101 - 108 = not used; 109 sink. This parameter can be used with modules `strmflow_in_out`, `muskingum`, and `muskingum_lake`, which are available in PRMS or PRMS5 simulation modes with the sole purpose of accumulating total flows for each segment type.

Parameters used when **model\_mode** = PRMS5 or GSFLOW5

#### **tmax\_allrain\_offset**

- Equals old parameter **tmax\_allrain** – **tmax\_allsnow**

#### **soil\_rechr\_max\_frac**

- Equals old parameter **soil\_rechr\_max** / **soil\_moist\_max**

#### **soil\_rechr\_init\_frac**



- Equals old parameter **soil\_rechr\_init / soil\_rechr\_max**
- soil\_moist\_init\_frac**
- Equals old parameter **soil\_moist\_init / soil\_moist\_max**
- ssstor\_init\_frac**
- Equals old parameter **ssstor\_init / sat\_threshold**
- sro\_to\_dprst\_perv**
- Equals old parameter **sro\_to\_dprst**
- dprst\_frac**
- Equals old parameter **dprst\_frac\_hru**

Parameters used when **model\_mode** = PRMS or GSFLOW

**tmax\_allrain**

- Replaced by **tmax\_allrain\_offset**

**soil\_rechr\_max**

- Replaced by **soil\_rechr\_max\_frac**

**soil\_rechr\_init**

- Replaced by **soil\_rechr\_init\_frac**

**soil\_moist\_init**

- Replaced by **soil\_moist\_init\_frac**

**ssstor\_init\_init**

- Replaced by **soil\_moist\_init\_frac**

**sro\_to\_dprst**

- Name change to **sro\_to\_dprst\_perv**

**dprst\_area** or **dprst\_frac\_hru**

- Replaced by **dprst\_frac**

## NEW VARIABLES

**strmflow\_in\_out, muskingum, muskingum\_lake**

- Added support for additional segment types using the parameter **segment\_type** that provides output by category. These are *flow\_to\_lakes*, *flow\_to\_ocean*, *flow\_to\_great\_lakes*, *flow\_out\_region*, *flow\_out\_NHM*, *flow\_in\_region*, *flow\_terminus*, *flow\_in\_nation*, *flow\_headwater*, *flow\_in\_great\_lakes*, *flow\_replacement*.

**intcp**

- *intcp\_changeover* and *basin\_changeover*

## REMOVED VARIABLES

- *cascade\_interflow, cascade\_dunnianflow, interflow\_max, cpr\_stor\_frac, pfr\_stor\_frac, gvr\_stor\_frac, soil\_moist\_frac, soil\_rechr\_ratio, snowevap\_aet\_frac, perv\_avail\_et, and cap\_upflow\_max*

### **SMALL CHANGES THAT DO NOT AFFECT ANY COMPUTATIONS**

Determination of Muskingum routing variables moved from source file muskingum.f90 to routing.f90 so that the muskingum and muskingum\_lake modules could share the same code.

### **PRMS UTILITIES**

- If an error is encountered reading a Parameter File an error message is issued and the file is no longer read instead of trying to continue reading the file.
- The delimiter between specification of multiple values on a line in a Parameter File was changed from a comma to a space. Trailing blanks cannot be specified on a line as this produces a read error.
- The end of a line for parameter values is determined by either a new line or null character instead of just a new line.
- Possible security issues addressed related mostly to buffer overflow and underflow.

### **MODFLOW Packages**

GSFLOW version 2.0.0 is based on MODFLOW-NWT version 1.1.4 and some additional changes made since this last release. MODFLOW-2005 source files used in MODFLOW-NWT were updated to reflect changes made for MODFLOW-2005 version 1.12.0. Since the last GSFLOW release (version 1.2.2), there has been one MODFLOW-NWT releases (version 1.1.4) and one MODFLOW-2005 release (version 1.12.0). Changes made to MODFLOW-NWT and MODFLOW-2005 are described in the release notes for those codes; users are encouraged to review those release notes in addition to the notes provided below.

#### **Well (WEL) package**

- Character variable text was initialized in PARSEWELLOPTIONS
- A bug was fixed that was setting IUNITRAMP to default value; an incorrect write statement was stating that PSIRAMP was also changed; however, it was not changing from user-specified value. The default value for PSIRAMP was changed to 0.10.

#### **Streamflow Routing (SFR2) Package**

- Subroutine CALC\_XSA was added to calculate cross-sectional area for MT3D-USGS. Smoothing of conductance in SFR used stream head and was changed to use depth. Added error handling for case of negative flows specified in headwater segments. Added variable IGRID to call list in subroutine SFR7AD.

### **Unsaturated-Zone Flow (UZF1) Package**

- A new option was included for specifying the layer to which UZF recharge is added (NUZTOP=4). If NUZTOP is specified as 4, then the values of IUZFBND are used to define the top of the unsaturated zone, and recharge is added to the uppermost layer in a column that contains a water table. The layer to which recharge is added is updated at the beginning of each new time step and is held constant during a time step.
- A small bug was fixed that was causing the counter on trailing waves to be off by one. This bug only affected model in very rare cases; but, this bug could cause the model to stop suddenly.
- The calculation for total applied runoff that is output to the UZF gage file option 4 was incorrect. This variable only is used for gage file output and does not affect any other calculated values.

### **Lake (LAK) Package**

- Error was fixed in calculation for lake volume for the linear case.
- The interval for which derivatives are smoothed to zero in the calculation of specified outflows from lakes was changed from a constant to a variable.

### **Basic (BAS) Package**

- The size of character variables was increased to print larger words to the LIST file budget table.

### **Drain Return Flow (DRT) Package**

- When a return cell went dry, the program failed to write a budget record for the COMPACT BUDGET option. This resulted in an incorrect number of records. Program was modified so that a zero value is written to the budget file for a return cell if it is inactive.

### **Link-MT3DMS (LMT) Package**

- Changes were made to account for negative values of FLOW in SFR input.
- Checks were added for DELT=0 before dividing by DELT.
- A change was made to make diversions from the last reach of a segment, rather than the first reach as was incorrectly assumed.

### **Gage Package**

- Added check to make sure SFR or LAK are active.

- A minor output problem occurred when writing output for lakes when the Lake Package input specified RNF as a negative value, which is used as a flag, and OUTTYPE = 1, 3, or 4. The Gage output file incorrectly included the negative value rather than the actual computed value of runoff to the lake. This problem was corrected. The model user does not need to do anything differently. Note, all model calculations were correct (and not affected by the fix) and that correct values for runoff to a lake were always printed in the main output (listing) file.

### **Upstream Weighting (UPW) Package**

- A warning was added indicating that IPHDRY is set to 1 (print HDRY) and observation packages are active. IPHDRY should be set to zero because if IPHDIY is set to 1 then observation values could erroneously be calculated using HDRY.

### **Seawater Intrusion (SWI2) Package**

- Added FIXEDZETA option, which fixes the zeta surfaces during the simulation and does not allow them to move.

### **Multi-Node Well (MNW2) Package**

- These changes were made for MODFLOW-2005 version 1.12 and updated into the version for NWT. These changes were copied from the file "readme\_MNW2.txt" included in the MODFLOW-2005 release.
- A bug was fixed that affected the calculation of intraborehole flow (initiated when PUMPLOC is not = 0) for output purposes only and only for certain conditions. These values are written to the MNWOBS file if QBHflag>0. Additional print statements were also added so that data on the location of the pump intake will always be written to the main listing file.
- The program will not calculate corrections for partial penetration of a MNW2 well if the losstype=SPECIFYcwc, in part because the required well radius is not specified in the input data for this losstype. If the input for a particular MNW2 well specifies losstype=SPECIFYcwc and PPFLAG>0, the code will reset PPFLAG to a value of 0 and print a related warning message.
- Code was added to check if the water table drops below the bottom of the open interval in a MNW2 node. If it did, that node is deactivated.
- Problems related to the partial penetration correction calculation have been reported for MNW2 nodes in convertible cells. To minimize these, the PPFLAG is

reset to 0 if the head in the well (hwell) declines to a level that only leaves less than 10% of the open interval saturated or if either hwell or the water table drops below the bottom of the open interval (in which case the node is also deactivated).

- A bug in the code for the case of a horizontal or slanted well and LOSSTYPE=GENERAL caused the code to ignore the specified value of "B" (the linear well-loss coefficient) and instead assumed that it was zero. This has been fixed. Note that the algorithm assumes that there is no directional dependence of B and that the specified value applies equally in all directions. This bug would have had only a very small effect on results in most cases.
- Write statements were modified to help assure that elevations of well screens (open intervals) were printed correctly. Penetration fractions values will be printed as "N/A" for cases where partial penetration calculations are not made.
- As described on p. 53 of the MNW2 documentation report (specifically, the last sentence describing both "QNDflag" and "QBHflag"), additional data will not be written if the well contains only one node. That is, both of these flags should be equal to 0 if the MNW well only includes a single node. If not, code added to the MNWI routines will detect this inconsistency and reset these flags to zero and write an information message in the main output file when this triggering condition is found.
- Several coding changes were made based on suggestions from Scott Boyce (USGS, California Water Science Center) and are labeled with his initials (seb).
- A bug was fixed for writing header information to the compact budget output file when no wells are active.
- Other minor format changes were made for the output files.

### **Version 1.2.2 (February 23, 2018)**

This version of GSFLOW is based on MODFLOW-NWT version 1.1.3 and PRMS version 4.0.3. A number of bug fixes and slight modifications have been made to the software for this release; these bug fixes and modifications that are more than simply cosmetic are described below, beginning with changes to the PRMS and GSFLOW Modules and then changes to the MODFLOW Packages. NOTE: Restart Files generated by previous versions of GSFLOW are not compatible with the current version, thus they must be regenerated.

The iteration method was altered to promote MODFLOW and PRMS to continue to iterate together until the MODFLOW solution converges. Previously, users could specify parameter **szconverge** that provided for discontinuing soil-zone computations prior to MODFLOW convergence if the maximum change in gravity drainage from the soil zone for all HRUs between successive iterations was less than **szconverge**. This option has been removed. Additionally, parameter **mnsziter**, the minimum number of `soilzone` iterations, was removed. Parameter **mxxziter**, the maximum number of `soilzone` iterations, is retained. It is recommended that the `soilzone` module iterate until MODFLOW converges by setting **mxxziter** to **MXITER** or **ITMX** as specified in the MODFLOW input. If some timesteps are taking many iterations while most are taking many fewer, users could experiment with reducing **mxxziter** to something like twice the value of the typical number of iterations, which might allow MODFLOW to converge more quickly. This change can result in noticeable differences with previous GSFLOW versions as the number of iterations to convergence may change on any timestep. Input PRMS Parameter Files that contain **mnsziter** and/or **szconverge** are downward compatible as these parameters are ignored. GSFLOW issues warning messages for parameters included in a PRMS Parameter File that are not needed; to turn this type of warning off, set control parameter **parameter\_check\_flag** to 0 as specified in the Control File.

The GSFLOW timestep budget computation was altered to simplify accounting for any flux change in groundwater discharge from MODFLOW cells to the soil zone of PRMS HRUs (MODFLOW variable **SEEPOUT**) between the values last used by PRMS and the final values calculated in the MODFLOW budget solution. The change in **SEEPOUT** is only applied to the storage in the associated soil-zone gravity reservoirs for each cell. Previously, if there was insufficient storage in gravity reservoirs to account for the flux change, water could be taken from preferential-flow and/or capillary reservoir storage if available in order to maintain a water balance. As the gravity reservoir storage is the primary point of coupling between PRMS and MODFLOW, only using this storage to account for the flux change was deemed consistent with the original intent of GSFLOW. The drawback is that the change permits storage in gravity reservoirs to go negative under some conditions such as at the beginning of a simulation if the gravity reservoirs are initialized to 0 and during very dry conditions in the middle of simulations. It is believed that the negative storages would be very small, such as less than -1.0 cubic meters as seen in the Sagehen model. The value considered round-off error for the flux change and set to 0 was changed from  $< \text{ABS}(1.0\text{E}-6)$  to  $\text{ABS}(\text{EPSILON}(0.0))$ , which is  $\text{ABS}(1.1920929\text{E}-07)$  with Intel Fortran.

Note about information printed to the screen during execution. There can be a large amount of information printed to the screen in terms of general information, warning messages, and error messages during initialization of a simulation. Sometimes this can make it difficult to see important error messages. There are several ways to reduce screen output. Set control parameter **parameter\_check\_flag** to 1 in the PRMS Control File to minimize warning messages about parameter values falling within the suggested range. Set control parameter **print\_debug** to -2 (minimum output) or -1 (less output). However, setting **parameter\_check\_flag** = 1 and **print\_debug** = 0 is good practice during initial model development as all warning and error

messages are available. But, once warnings are deemed ok, **parameter\_check\_flag** should be set to 0 and **print\_debug** to -1 or -2. Additionally, increasing the value of control parameter **rpt\_days** can be used to reduce screen output.

## PRMS and GSFLOW Modules

The PRMS version (4.0.3) included in GSFLOW version 1.2.2 is based on PRMS-IV as documented in Markstrom and others (2015). The version 4.0.3 release corrected major bugs in the `potet_pm` and `potet_pt` modules and minor bugs in the `soilzone` and `gwflow` modules. Screen and Model Output File output updated for readability and output of additional information. Removed deprecated farfield computations (that is, flow leaving the model-domain boundary not through the stream network), variables: *basin\_sroff\_farflow*, *basin\_szfarflow*, *basinsrofffarflow*, *basinszfarflow*, *strm\_farfield*. See the file “Update of PRMS PET modules.pdf” in the “doc\Related reports” directory for critical updated documentation on the equations used in the `potet_jh`, `potet_hs`, `potet_pt`, and `potet_pm` modules.

### BUG FIXES – by module:

#### `snowcomp`

- When a snowpack is melting and there is a new snowfall, the code is supposed to save the point on the depletion curve (variable *snowcov\_areasv*) and then deplete the snowpack from **snarea\_curve(11,k)** over the subsequent time steps until the snow covered area is less than or equal to *snowcov\_areasv* on the basis of linear interpolation. See Figure 1-4, page 97 of the PRMS-IV documentation report (TM6-B7, Markstrom and others, 2015) for a depiction of how the code was supposed to compute snow-water equivalent (SWE) using a depletion curve after a secondary snowfall. However, *snowcov\_areasv* was set to **snarea\_curve(11,k)**, the maximum value of a snow depletion curve. This fix can change results of the snowpack depletion for secondary snowfalls as depletion begins at the maximum value of the depletion curve instead of returning to the point of departure from the depletion curve from which it was melting prior to the snowfall. Thus, there will be no change for many snowpacks, but, noticeable change to results for some. Variable *frac\_swe* was not computed for all time steps, this was corrected, and the variables was changed to single precision; this change did not affect other computations.

#### `potet_pt`

- The computation of the net long wave radiation was corrected. See “Update of PRMS PET modules.pdf” file in the “doc\Related reports” directory for corrections to PRMS-IV documentation report.

#### `potet_pm`

- The computation of the net long wave and net radiation coefficients used to compute potential ET were corrected. See “Update of PRMS PET modules.pdf” file in the “doc\Related reports” directory for corrections to PRMS-IV documentation report.

srunoff

- The computation of pervious and impervious capture of pervious and impervious surface runoff into depressions did not account for the fraction of pervious and impervious to compute actual inflow, which lead to the possibility of excess water to the stream network.

muskingum

- If **K\_coef** was set < 1.0, it was possible to get a divide by 0 under rare conditions, this was corrected.

temp\_dist2

- Values for parameter **tmax\_adj** and **tmin\_adj** were not read from the Parameter File and were likely set to zero or very small values.

soilzone

- Changed declared dimensions from **nhru** to **one** for variables *basin\_cpr\_stor\_frac*, *basin\_gvr\_stor\_frac*, *basin\_pfr\_stor\_frac*, *basin\_soil\_lower\_stor\_frac*, *basin\_soil\_rechr\_stor\_frac*, and *basin\_sz\_stor\_frac*. This change does not affect any computations, but, could cause unpredictable results for output of these variables in statvar and animation files and runtime graphs.
- Computation of *basin\_pfr\_stor\_frac* was computed incorrectly using *pref\_flow\_stor* instead of *pfr\_stor\_frac*. This does not affect any other computations.

gwflow

- The determination of whether to add storage on the basis of the value of **gwstor\_minarea** is done after adding recharge instead of before.

basin

- If an HRU had open and closed surface-depression storage portions, computations were incorrect; this was corrected.

gsflow\_budget

- Changed declared dimension from **nhru** to **nsegment** for variable *streamflow\_sfr*. This change does not affect any computations, but could cause unpredictable results for output of this variable in statvar and animation files and runtime graphs.

## **SMALL CHANGES THAT DO NOT AFFECT ANY COMPUTATIONS**

gsflow\_prms

- Updated output to screen and to the model output file for improved readability and added output of the Parameter File name.

cascade

- Removed checks for specification of farfield flow as farfield computations are not supported.

subbasin

- Changed units in variable descriptions for *subinc\_wb* and *subinc\_deltastor* from cfs to inches.

map\_results

- Messages for incomplete or excess accounting for mapping between HRU map and target map includes more information.

basin

- Summary statistics for areal portions and date and times reformatted.



## NEW FUNCTIONALITY

`nsub_summary`

- New summary output module that operates similarly to `nhru_summary` and with similar control parameters except that it is used to write values of variables dimensioned with **nsub**.

`nsegment_summary`

- New summary output module that operates similarly to `nhru_summary` and with similar control parameters except that it is used to write values of variables dimensioned with **nsegment**.

`basin_summary`

- New summary output module that operates similarly to `nhru_summary` and with similar control parameters except that it is used to write values of variables dimensioned with **one**.

`potet_pt`

- Allows humidity data to be specified using new parameter **humidity\_percent** that has maximum dimensions **nhru** by **nmonths** as an alternative to specification of humidity in a CBH file. Note, previous versions of the `potet_pt` module did not require humidity data.

## NEW VARIABLES

Added variable `basin_swrad`, which is set equal to `basin_potsw`. This change impacts modules `ccsolrad`, `ddsolrad`, `climate_hru`, and `climateflow`.

Added subbasin variables: `subinc_rain`, `subinc_snow`, `subinc_stor`, `subinc_recharge`, `subinc_szstor_frac`, and `subinc_capstor_frac`.

Added `basin_sum` variables: `basin_swrad_yr`, `basin_swrad_tot`, and `basin_swrad_mo`, which are added to summaries in the **model\_output\_file** on the basis of selected print options.

Added `soilzone` variables: `cascade_dunnianflow`, `cascade_interflow`, `grav_gwin`, and `interflow_max`

## MODFLOW Packages

GSFLOW version 1.2.2 is based on MODFLOW-NWT version 1.1.3, as well as updates that have been made to MODFLOW-2005 version 1.12.0. This means that MODFLOW-2005 source files used in MODFLOW-NWT were updated to reflect changes made for MODFLOW-2005 version 1.12.0. Since the last GSFLOW release (version 1.2.1), there has been one MODFLOW-NWT releases (version 1.1.3) and one MODFLOW-2005 release (version 1.12.0). Changes made to MODFLOW-NWT and MODFLOW-2005 are described in the release notes for those codes; users are encouraged to review those release notes in addition to the notes provided below.

MODFLOW-NWT Current Version, 1.1.3 (August 1, 2017):

Source files that were modified for this release are: gwf2uzf1\_NWT.f, gwfuzfmodule\_NWT.f, gwf2sfr7\_NWT.f, gwfsfrmodule\_NWT.f, gwf2lak7\_NWT.f, gwf2gag7\_NWT.f, gwf2upw1.f, gwf2wel7\_NWT.f. Packages LMT, SWI, and SWT were added for use in MODFLOW-only simulations.

Specific notes on the MODFLOW Packages:

#### Unsaturated-Zone Flow (UZF) Package

Fixed bug that occurred when IUZFOPT=0 and element 0 accessed in array DELSTOR. Fixed keyword options to support old format. Fixed bug in UZ initialization to allow multiple consecutive steady state stress periods. Fixed bug causing UZF land surface to be incorrectly set for cells underlying lake cells.

#### Streamflow Routing (SFR2) Package

Keyword options were modified to allow for backward compatibility of previous input formats of keywords, including single line lists of keywords. A bug was fixed that affects models that use the LOSSFACTOR option for reducing streambed hydraulic conductivity for losing streams. This bug fix includes modifications that were made after the release of MODFLOW-NWT Version 1.1.3.

#### Lake (LAK) Package

Fixed array index from DELVOLLAK(NSSAR) to DELVOLLAK(NLAKES). Fixed Lake Package derivatives for better solutions. Fixed instability issue with Lake Package for small lakes and large surface inflow and outflow.

#### Gage (GAG) Package

Added check to make sure the SFR Package is active if stream gages are input to the GAG Package. Previously, a memory access error would occur if the SFR2 Package was inactive and stream gages were specified within the GAG Package input file.

#### Multi-Node Well (MNW2) Package

Initialized variable Hwell. Fixed reference to lbotm in botm arrays used for models with quasi-confining units.

#### Link-MT3DMS (LMT) Package

Changes to the LMT Package since the release of MODFLOW-NWT 1.1.3: Terms appearing in either SFR or LAK were removed from the LMTMODULE and instead placed in SFRMODULE or LAKMODULE. Added IGWET to the LMTMODULE and allocated the variable to avoid memory overwrite errors. Bug fix for binary output in LMT (an extra term was being written that was

causing problems to the FMI package in MT3D-USGS). Fixed a bug in LMT related to the linkage of groundwater discharge (or runoff) to a sink (that is, not connected to surface-water through IRUNBND). Bug fix to LMT to use KPER and KSTP from PRMSMODULE instead of GSFMODFLOW.

### Upstream-Weighting (UPW) Package

If the variable IPHDRY was set to 1 for outputting Hdry for dry cells, then Hdry could be used by any of the OBS Packages to calculate observation values. The code was modified to output a warning to the LIST file command window if any OBS Packages are active and IPHDRY is greater than zero.

### Well (WEL) Package

Added ability to reuse the same well tabfile for more than one well. Changed reading the tabfiles to allow comment lines in tabfiles. Modified output of pumping rates to LST file to separate this output from output that lists wells with reduced pumping. Modified keyword input formats to support backward compatibility of previous keyword input formats. Character variable PHIRAMP can be used instead of SPECIFY for inputting PHIRAMP and optional output file unit number for writing reduced pumping rates. Thus, a phiramp value and outfile file unit number can be specified, respectively, in the first non-comment record in the WEL input file as:

```
OPTIONS  
phiramp 0.1 15  
END
```

### **Version 1.2.1 (October 1, 2016)**

This version of GSFLOW is based on MODFLOW-NWT version 1.1.2, MODFLOW-2005 version 1.11.0, and PRMS version **4.0.2**. A number of bug fixes and slight modifications have been made to the software for this release; those bug fixes and modifications that are more than simply cosmetic are described below, beginning with changes to the PRMS Modules and then progressing to changes to the MODFLOW Packages and GSFLOW Modules.

This version includes an update to the 'gsflowAnalysis.xls' Excel workbook that was distributed with previous versions of GSFLOW. The new workbook is called 'GSFLOW\_WBAnalysis\_SeriesSEE.xlsm' and is found in the 'water-budget utility' directory of the release. The update was done to better evaluate model results with the data-viewing and data-manipulation capabilities provided by the SeriesSEE Excel Add-In. The utility can be used during model construction, calibration, or application to evaluate simulation results. As part of the update, the definitions of the various GSFLOW water-budget output variables have been revised. The revised water-budget components are illustrated in the 'Budget\_Diagrams.pdf' and the updated variable names are defined in 'Definitions of Budget Variables.pdf.' Both files are located in the 'water-budget utility' directory. Users are encouraged to review the Budget

Diagrams, which provide depictions of the inflows, outflows, and storage processes of the major water-budget compartments simulated by GSFLOW.

## PRMS Modules

The PRMS version (4.0.2) included in GSFLOW version 1.2.1 is based on PRMS-IV as documented in Markstrom and others (2015). The version 4.0.2 release added new parameters and variables, corrected bugs, added more checks for valid input values, included general code clean up (mostly to reduce mixed floating-point computations by changing some variables to double precision, some to single precision), and added FORTRAN intrinsic functions to convert variables prior to mixed-precision computations. Detailed descriptions of changes made for PRMS version 4.0.2 are described in the PRMS release notes included with the PRMS distribution ([http://wwwbrr.cr.usgs.gov/projects/SW\\_MoWS/PRMS.html](http://wwwbrr.cr.usgs.gov/projects/SW_MoWS/PRMS.html)).

Changes in the specification of user inputs are reported as updates to tables in the Users' Manual (tables 2, 1-2, 1-3, and 1-5) at [ftp://brrftp.cr.usgs.gov/pub/mows/software/prms/4.0.2/PRMS\\_tableUpdates\\_4.0.2.pdf](ftp://brrftp.cr.usgs.gov/pub/mows/software/prms/4.0.2/PRMS_tableUpdates_4.0.2.pdf)

**Some** input and output options that are available in PRMS-IV are not available in the current GSFLOW release, such as those related to the `strmflow_lake` module. Additional changes made to PRMS-IV that are relevant to GSFLOW simulations are described for the GSFLOW version 1.2 release beginning on page 21 of this document.

**Significant change from previous versions:** The values of all parameters specified in the PRMS Parameter File are now checked to be sure that they fall within the suggested minimum and maximum range. If values are specified outside the range, an error message is issued, and the simulation stops. If the user wants to specify values out of the range, set control parameter **parameter\_check\_flag** = 0 to deactivate these checks.

The following sections highlight additional important changes.

### **Bug Fixes by Module**

Fix to Surface-Depression Storage:

- In the previous version of the software (1.2.0), the Surface-Depression Storage functionality did not include gravity drainage (seepage) in the computation of total recharge (that is, output-variable *recharge*). This has been corrected and Surface-Depression Storage computations now correctly include the seepage term.

`basin` module:

- Corrected code to ensure a divide by zero is not permitted for the condition that there are closed depressions but not open depressions; that is, if any values for parameter **dprst\_frac\_open** are specified = 0.

- If the first value of parameter **dprst\_area** was specified  $< 0$  or not included in the Parameter File, the values of **dprst\_frac\_hru** (default value = 0) were ignored if specified. Thus, if **dprst\_frac\_hru** was not included in the Parameter File no surface-depression storage would be simulated; this check should have been reversed. Use of parameter **dprst\_area** is now deprecated, so users should now use **dprst\_frac\_hru** and specify values  $\geq 0$ . The default value of **dprst\_frac\_hru** is now -1.0.

precip\_laps module:

- Arrays for parameters **rain\_adj\_lapse** and **snow\_adj\_lapse** were not allocated, causing application to fail.

climate\_hru module:

- Variable *basin\_obs\_ppt* was set to 0 when it should only be computed when precipitation values are input in CBH Files; thus, an error occurred if parameter **precip\_module** was not specified equal to `climate_hru`.
- 

ide\_dist module:

- Computations of inverse distance and elevation are allowed to be less than 0 for precipitation computations to be consistent with computations for temperature.

potet\_hs module:

- The kt coefficient was first being computed each day using an equation based on average temperature as described in [http://www.zohrabsamani.com/research\\_material/files/Hargreaves-samani.pdf](http://www.zohrabsamani.com/research_material/files/Hargreaves-samani.pdf). Then, this value was multiplied by the **hs\_krs** parameter. Now, only the **hs\_krs** parameter is used in the Hargreaves-Samani equation, which matches the PRMS-IV documentation. The kt coefficient equation can be used to estimate the **hs\_hrs** parameter:  $\text{coef\_kt} = 0.00185 * (\text{temp\_dif} ** 2) - 0.0433 * \text{temp\_dif} + 0.4023$ , where *temp\_diff* is the difference between the HRU maximum and minimum temperature in units of degrees Celsius. See “Update of PRMS PET modules.pdf” in the “doc/Related reports” subdirectory for more details.

potet\_pt module:

- The code incorrectly used the average HRU temperature in degrees Fahrenheit when it was supposed to be in degrees Celsius in one equation. See “Update of PRMS PET modules.pdf” in the “doc/Related reports” subdirectory for more details.

potet\_pm module:

- The formulation of the Penman-Monteith equation has been updated to include a crop coefficient. See “Update of PRMS PET modules.pdf” in the “doc/Related reports” subdirectory for more details.

snowcomp module:

- Added check to be sure *snowcov\_area* is not equal to zero when *pkwater\_equiv* is greater than 0. This would be very rare and only possible when the second value of a snow-depletion curve was specified equal to zero.
- Checks were added to be sure *pkwater\_equiv* is set to 0.0 if it is computed as a very small negative value, which would be very rare.
- Added check for when *pkwater\_equiv* < 1.0E-10 and *snowcov\_area* > 0; if true, set *snowcov\_area* to 0. This is possible when the energy is enough to melt the snowpack on the previous time step. This bug affected computations for impervious and surface-depression storage evaporation for days without snow and snow depletion curves that specified snow-covered area exists when the snow-water equivalent is equal 0.
- In calin function, *snowcov\_area* was set to 0 when it should not be because it is the snow cover after adding precipitation and before any melt or sublimation; this condition affects computations for impervious and surface-depression storage evaporation for days with snow.
- If snowpack exists and the snowpack density (*pk\_den*) <= 0, be sure *pk\_den* and the snowpack depth (*pk\_depth*) have a value based on parameter **den\_max** in run function and calin function; this condition would be rare.
- In routine calin, added check for the value of *freeh2o - pwcap > pkwater\_equiv*; if so, use the value of *pkwater\_equiv*. This condition would be rare.
- In routine calin, the local variable *pk\_ice* did not have a value if *snowcov\_area* <= 0; if true, it is set to 0. This condition would be rare.

*srunoff\_smidx* and *srunoff\_carea* modules:

- Variable *contrib\_fraction* was declared as dimension **one** and data type double when it should be dimension **nhru** and data type single. This error could have caused memory problems if the variable was output in a Statistics Variable (statvar) or Animation File, or using the PRMS GUI runtime plots, but would not affect any computations.

*soilzone* module:

- Computation of variable *soil\_lower\_ratio* was set incorrectly to *soil\_moist/soil\_moist\_max* instead of *soil\_lower/soil\_lower\_stor\_max* and values of *soil\_lower\_ratio* for lake and inactive HRUs were not initialized to 0. No other computations are affected.
- In the compute\_soilmoist routine, the check for infiltration water in excess of **soil\_moist\_max** minus *soil\_to\_gw* (local variable *excs*) was > *Infil* should have been a check for *excs > Infil \* perv\_frac* as *excs* is computed for the whole HRU area and *infil* for only the pervious area on an HRU; this condition was not likely to have occurred.
- Make sure any flow from gravity to preferential-flow reservoirs is set to 0 or current value (previous versions could have used value from previous HRU if current HRU in loop does not have preferential flow reservoir).
- Variables *recharge* and *sm2gw\_grav* did not include *dprst\_seep\_hru*

*subbasin* module:

- Subbasin storage did not include surface-depression storage.

routing module:

- Variables *seginc\_potet*, *seginc\_gwflow*, *seginc\_ssflow*, *seginc\_sroff*, and *seginc\_swrad* are not computed if the cascading-flow option was active, which was an error if parameter **hru\_segment** was not specified.
- The value of *seg\_lateral\_inflow* was not set correctly when the cascading-flow option was active; it is now set to *strm\_seg\_in*.

map\_results module:

- Yearly output was not computed when parameter **mapvars\_freq** = 5.
- Corrected IF blocks that determine whether or not parameters **gvr\_cell\_pct** and **gvr\_hru\_id** were needed; **gvr\_cell\_pct** needed when **nhru** not equal **ngwcell** and **gvr\_hru\_id** needed when **nhru** not equal **nhru**.

water\_balance module:

- Full array for *hru\_sroffp* and *hru\_sroffi* instead of HRU value printed for water-budget issue for **srunoff** with cascades active.
- Variable *soil\_to\_ssr* was not included in HRU **soilzone** water-budget computation. This variable is needed because the variable *cap\_waterin*, actual water into capillary reservoir, replaced *cap\_water\_maxin*, the maximum potential water into the capillary reservoir.

nhru\_summary module:

- Removed duplicate allocate of variable Dailyunit; was only a problem if daily output was requested.

basin\_sum module:

- The value of the yearly observed streamflow or monthly value of computed basin streamflow and monthly observed streamflow was not printed for **print\_type** = 2.
- Detailed output did not have the right line length, thus missing a value.
- Yearly detailed output now includes evaporation for lakes and interception storage.

### **Changes That Might Produce Slight Changes in Associated Computations—General:**

- Some single-precision variables were changed to double-precision variables and vice versa; also, most modules now use FORTRAN intrinsic functions to explicitly designate mixed-precision computations. These changes are intended to limit the possibilities of different results on different computers and compilers, to provide more consistent floating-point comparisons, and to have more consistent round-off issues. These updates could change memory requirements and execution time very slightly. Modules affected: *prms\_time*, *obs*, *cascade*, *ccsolrad*, *ddsolrad*, *climate\_hru*, *temp\_1sta*, *temp\_laps*, *temp\_dist2*, *precip\_1sta*, *precip\_laps*, *precip\_dist2*, *ide\_dist*, *xyz\_dist*, *frost\_date*, *potet\_hamon*, *potet\_hs*, *potet\_jh*, *potet\_pan*, *potet\_pm*, *potet\_pt*, *intcp*, *snowcomp*, *srunoff\_smidx*, *srunoff\_carea*, *soilzone*, *gwflow*,

routing, water\_balance, nhru\_summary, map\_results, subbasin, climateflow, and basin.

- Computation of saturation vapor pressure for module `potet_pm` now uses an equation by Irmak and others (2012; Journal of Hydrology, v. 420-421, p. 228), to be consistent with module `potet_pt`. This can reduce execution time.
- Small values ( $>0.0$  and  $< 1.0E-05$ ) of precipitation are used in computations; previously these values were assumed to be below round-off tolerance and set to 0. This affects modules `obs`, `precip_1sta`, `climate_hru`, `ide_dist`, `xyz_dist2`, and `precip_laps`.
- Small values ( $>0.0$  and  $< 1.0E-06$ ) of computed potential evapotranspiration were considered to be round-off error and set to 0; now those values are used in computations. This change affects modules `potet_hamon`, `potet_hs`, `potet_jh`, `potet_pan`, `potet_pm`, and `potet_pt`.
- Small values ( $>0.0$  and  $< 1.0E-04$ ) specified for `hru_percent_imperv` and `dprst_area` are used in computations; previously these values were assumed to be below round-off tolerance and set to zero.
- Module `cascade`: changed check for excess GWR cascade fraction so that any values  $> 1$  set to 1 instead of only  $> 1.00001$ . This change makes the check consistent with the HRU cascade fraction check.
- Module `snowcomp`:
  - Instead of using  $< -1.0E-10$  to check for round-off issues in some computations,  $< 0.0$  is now used. Instead of using  $> 1.0E-06$  to check for round-off issues in some places,  $> 1.0E-09$  is now used.
  - Values of snowpack water equivalent (`pkwater_equiv`) computed between 0.0 and  $1.0E-09$  were considered to be round-off error and set to 0.0; these values are now used.
  - Values of `pkwater_equiv`  $< 0.0$  are set to 0.0 with a warning message printed when control parameter `print_debug`  $> -1$ . This condition accounts for negative round-off error due to mixed precision computations and may occur under rare conditions.
- Surface depression computation order changed to original as documented in PRMS-IV report; that is, evaporation is computed prior to spillage and seepage.
- `climateflow` module: Small values ( $>0.0$  and  $< 1.0E-06$ ) of computed mixed precipitation were considered to be round-off error and the event was set to all snow or all rain depending on the precipitation form, now those values are used in computations.

## **New Capabilities, Output Changes, and Computations Removed**

General changes:



- Code related to computations of farfield flows (that is, flow leaving the model-domain boundary not through the stream network) is deprecated and will be removed for the next GSFLOW release.
- Modules with updates to ERROR messages, WARNING messages, declaration descriptions (including suggested minimum values), and/or comments: *climate\_hru*, *climateflow*, *cascade*, *utils\_prms*, *snowcomp*, *srunoff*, *soilzone*, *routing*, *ide\_dist*, *obs*, *xyz\_dist*, *water\_balance*, and *potet\_jh*

basin module:

- Use parameter **hru\_segment** if PRMS streamflow routing is active even if using cascades
- Don't adjust *hru\_percent\_imperv* or *dprst\_frac\_hru*; if they add up to > 0.999 of the HRU area, now always an ERROR

climateflow module:

- Note: *basin\_potsw* is misnamed as it is not a potential value; it is the area-weighted average of actual solar radiation (variable *swrad*).

cascade module:

- New functionality: allow groundwater-reservoir cascades to be equal to HRU cascades with **cascadegw\_flag** = 2.

gwflow and cascade modules:

- Added option to allow GWRs to be swales with new control parameter **gwr\_swale\_flag** (0 = not allowed; 1 = groundwater flow routed to groundwater sink; 2 = groundwater flow routed to stream network).

xyz\_dist and ide\_dist module:

- Error message for invalid values of **tsta\_nuse** or **psta\_nuse** corrected to refer to correct parameter name instead of having temp\_nuse.

ide\_dist module:

- Use any value of precipitation > 0 instead of only > 1.0E-6; previously these small values were considered as round-off error and set to 0.
- Don't set *dat\_dist* or *dat\_elev* to 0 if computed < 1.0E-6, as 0 is a valid value.

ccsolrad module:

- Removed restart subroutine so that *ccsolrad* can be used in a restart simulation if *ddsolrad* was used for the antecedent simulation. The switch from *ddsolrad* to *ccsolrad* is still allowed.

snowcomp module:

- Code added to initialize snow states based on *snowpack\_init* and related parameters in the "init" procedure.

- Warning messages about small negative values of *pkwater\_equiv* are printed if **print\_debug**>-1; changes in the code should prevent the negative values that were possible in previous versions.

intcp module:

- Removed letting canopy intercept precipitation < 1.0E-5 above storage capacity; these small values are left in the canopy.

soilzone module:

- Reset *slow\_stor* and *pref\_flow\_stor* when using restart option just in case values for parameters **sat\_threshold** and **pref\_flow\_den** were changed.

gwflow module:

- Use any value of **gwstor\_min** instead of only > 1.0E-6; previously these small values were considered as round-off error and set to 0.

routing module:

- Compute total area associated with the stream network; some HRUs are inactive or swales so *segment\_area* can be less than *basin\_area*.

basin\_sum module:

- Labeled first value of reports as initial storage.
- Added print of water balance values to reports when **print\_type** = 1
- Added print of *basin\_intcp\_stor* and *basin\_lakeevap\_yr* to yearly report when **print\_type** = 2
- Replaced old FORTRAN line-print page control in column 1 to a blank

map\_results module:

- Stop if negative mapping fraction specified.
- Allow values > 0.0 and 1.0E-06 for parameter **gvr\_cell\_pct** instead of treating them as 0.0.

## MODFLOW Packages

GSFLOW version 1.2.1 is based on MODFLOW-NWT version 1.1.2, as well as updates that have been made to MODFLOW-2005 version 1.11.0. This means that MODFLOW-2005 source files used in MODFLOW-NWT were updated to reflect changes made for MODFLOW-2005 version 1.11.0. Since the last GSFLOW release (version 1.2.0), there have been three MODFLOW-NWT releases (versions 1.1.0, 1.1.1, and 1.1.2) and no MODFLOW-2005 releases. Changes made to MODFLOW-NWT and MODFLOW-2005 are described in the release notes for those codes; users are encouraged to review those release notes in addition to the notes provided below.

This release provides support for the new transport model called MT3D-USGS. Changes to MODFLOW-NWT to support MT3D-USGS were made to the source file *lmt8\_NWT.f*. These

changes include writing output for the UZF, SFR2, and LAK7 Packages that is required for simulating transport in the unsaturated zone, streams, and lakes. Refer to the MT3D-USGS documentation report for details (Bedekar, V., Morway, E.D., Langevin, C.D., Tonkin, M.T., 2015, MT3D-USGS version 1: a U.S. Geological Survey release of MT3DMS updated with new and expanded transport capabilities for MODFLOW: U.S. Geological Survey Techniques and Methods 6-A53, variously paginated).

Source files that were modified for this release are: gwf2uzf1\_NWT.f, gwfuzfmodule\_NWT.f, gwf2sfr7\_NWT.f, gwfsfrmodule\_NWT.f, gwf2lak7\_NWT.f, NWT1\_gmres.f90, gwf2swr7.f, gwf2swr7util.f, gwf2mnw27\_NWT.f, gmres.f90, NWT1\_solver.f and NWT1\_xmd.f, and lmt8\_NWT.f.

#### Specific notes on the MODFLOW Packages:

##### Upstream-Weighting (UPW) Package:

An error was corrected in the calculation of the derivative of the conductance equation during complete wetting of a cell. Testing using several problems indicated that this change has minimal effects on the solution.

##### Newton-Solver (NWT) Package:

Previous versions of MODFLOW-NWT reported a warning when the difference between a specified cell top and cell bottom was less than  $100 \times \text{Thickfact}$ , where Thickfact is an input variable specified within the NWT solver input file. These cells were set to inactive by setting IBOUND=0. This condition is now treated as an error and the model will stop if  $\text{TOP} - \text{BOT} < 100 \times \text{Thickfact}$ .

The bug found in the UPW Package also required a fix in the NWT Package for the calculation of the derivative of the conductance equation during complete wetting of a cell.

A minor memory-allocation error was fixed in GMRES that affected compilations using the gfortran compiler.

Default solver-input values for the xmd solver (Linmeth=2) were modified to improve convergence. Solver input values for the SIMPLE, MODERATE, and COMPLEX default options are:

##### SIMPLE:

DBDTHETA	=	0.97
DBDKAPPA	=	0.0001
DBGAMMA	=	0.0
MOMFACT	=	0.0
BACKFLAG	=	0
MAXBACKITER	=	20
BACKTOL	=	1.5
BACKREDUCE	=	0.97

```

IACL          = 1
NORDER       = 0
LEVEL        = 1
NORTH        = 5
IREDSYS      = 1
RRCTOLS      = 0.0
IDROPTOL     = 1
EPSRNS       = 5.0e-3
HCLOSEXMD    = 1.0e-3
MXITERXMD    = 50

```

**MODERATE:**

```

DBDTHETA     = 0.90
DBDKAPPA     = 0.00001
DBGAMMA      = 0.0
MOMFACT      = 0.1
BACKFLAG     = 0
MAXBACKITER  = 20
BACKTOL      = 1.1
BACKREDUCE   = 0.9
IACL         = 1
NORDER       = 0
LEVEL        = 1
NORTH        = 10
IREDSYS      = 1
RRCTOLS      = 0.0
IDROPTOL     = 1
EPSRNS       = 5.0e-3
HCLOSEXMD    = 1.0e-3
MXITERXMD    = 100

```

**COMPLEX:**

```

DBDTHETA     = 0.85
DBDKAPPA     = 0.00001
DBGAMMA      = 0.0
MOMFACT      = 0.1
BACKFLAG     = 1
MAXBACKITER  = 50
BACKTOL      = 1.1
BACKREDUCE   = 0.7
IACL         = 2
NORDER       = 0
LEVEL        = 15
NORTH        = 1
IREDSYS      = 1
RRCTOLS      = 0.0
IDROPTOL     = 1
EPSRNS       = 1.0e-3
HCLOSEXMD    = 1.0e-4
MXITERXMD    = 200

```

**Streamflow-Routing (SFR2) Package:**

(1) The input format for specifying character-variable options has changed. Rather than specifying character-variable options in a single line in a particular order, each character-

variable option is specified on a separate line. If additional input is required along with the character-variable option, then this value is specified on the same line as the character-variable option separated by one or more spaces. Options must be preceded with the "OPTIONS" specification and followed by the "END" specification. Characters can be specified as upper or lower case.

Optional character variables for SFR2 in any order:

```
OPTIONS  
[REACHINPUT]  
[TRANSROUTE]  
[TABFILES Numtab Maxval]  
[LOSSFACTOR Factor]  
END
```

New Data Set 1C:

```
[LOSSFACTOR Factor]
```

Definitions for new character-variable option:

**LOSSFACTOR** -- An optional character variable. When **LOSSFACTOR** is specified, the real variable **Factor** is multiplied by **STRHC1** or **Hc1fact** and **Hc2fact** to calculate seepage loss from streams. Calculation of groundwater seepage to streams is unchanged.

(2) Other changes: Some variables in the SFR2 Package were initialized; some variables were changed to arrays for use in MT3D-USGS; and an access violation was fixed.

Unsaturated-Zone Flow (UZF) Package:

(1) Some variables in the UZF Package for calculating runoff were initialized; a minor bug was corrected that relates to simulating unsaturated-zone flow beneath lakes; and a floating-point exception was fixed.

(2) A new function was added for simulating groundwater evapotranspiration (ET). This function simulates a constant ET rate over the extinction depth rather than linearly reducing ET as groundwater head decreases. The ET is smoothly reduced to zero using the same polynomial function used to reduce pumping in drying cells (Niswonger and others, 2011). ET is smoothly reduced as groundwater head drops to the extinction depth. The smoothing interval is specified as a factor of the extinction depth.

(3) New Options were added to UZF1 to allow the hydraulic conductivity used to calculate rejected infiltration and surface leakage to be different than the vertical hydraulic conductivity of the unsaturated zone (VKS).

(4) The input format for specifying character-variable options has changed. Rather than specifying character-variable options in a single line in a particular order, each character-

variable option is specified on a separate line. If additional input is required along with the character-variable option, then this value is specified on the same line as the character-variable option separated by one or more spaces. Options must be preceded with the "OPTIONS" specification and followed by the "END" specification. Letters can be specified as upper or lower case.

Optional character variables for UZF1 in any order:

```
OPTIONS
[SPECIFYTHTR]
[SPECIFYTHTI]
[NOSURFLEAK]
[SPECIFYSURFK]
[REJECTSURFK]
[SEEPSURFK]
[ETSQUARE smoothfact]
[NETFLUX unitrech unitdis]
END
```

Definitions of new variables:

**SPECIFYSURFK** -- An optional character variable. When **SPECIFYSURFK** is specified, the variable **SURFK** is specified in Data Set 4b.

**REJECTSURFK** -- An optional character variable. When **REJECTSURFK** is specified, variable **SURFK** instead of **VKS** is used to calculate rejected infiltration. **REJECTSURFK** is included only if **SPECIFYSURFK** is included.

**SEEPSURFK** -- An optional character variable. When **SEEPSURFK** is specified, variable **SURFK** instead of **VKS** is used to calculate surface leakage. **SEEPSURFK** is included only if **SPECIFYSURFK** is included.

**ETSQUARE** -- An optional character variable. When **ETSQUARE** is specified, groundwater ET is simulated using a constant potential ET rate, and is smoothed over a specified smoothing interval. This option is recommended only when using the NWT solver.

**smoothfact** -- An optional real variable specified if **ETSQUARE** is specified. For example, if the interval factor (**smoothfact**) is specified as **smoothfact =0.1** (recommended value), then the smoothing interval will be calculated as: **SMOOTHINT = 0.1\*EXTDP** and is applied over the range for groundwater head (**h**):

$h < \text{CELTOP-EXTDP}$ , ET is zero;  
 $\text{CELTOP-EXTDP} < h < \text{CELTOP-EXTDP+SMOOTHINT}$ , ET is smoothed; and  
 $\text{CELTOP-EXTDP+SMOOTHINT} < h$ , ET is equal to potential ET.

`NETFLUX` -- An optional character variable. When `NETFLUX` is specified, the sum of recharge (units of cubic length per time) and the sum of discharge (units of cubic length per time) is written to separate unformatted files using module `UBDSV3`. `Unitrech` and `Unitdis` are the unit numbers to which these values are written when "SAVE BUDGET" is specified in Output Control. Values written to `Unitrech` are the sum of recharge values for the UZF, SFR2, and LAK Packages, and values written to `Unitdis` are the sum of discharge values for the UZF, SFR2, and LAK Packages. Values are averaged over the period between output times.

#### Data Set 4B:

```
[SURFK (NCOL, NROW)] -- U2DREL
```

`SURFK` -- An optional array of positive real values used to define the hydraulic conductivity (units of length per time). `SURFK` is used for calculating the rejected infiltration and/or surface leakage. If `SURFK` is set greater than `VKS`, then it is set equal to `VKS`.

#### Lake (LAK) Package:

Some variables were changed to arrays in order to save data for MT3D-USGS. A minor bug was corrected that relates to simulating unsaturated-zone flow beneath lakes.

#### Well (WEL) Package

(1) A bug was fixed that sets pumping applied to inactive cells to zero. This bug only affects results printed to the cell-by-cell budget file. (2) A small error was fixed in the calculation of the derivative used for smoothing the pumping rate to zero for drying cells. (3) A bug was fixed that would cause the pumping rate to be calculated incorrectly when using the tabfile option and the time values specified in the tabfile did not extend to the end time of the simulation.

(4) As a consequence of the following changes to the Well Package input structure, the package no longer supports previous input files that read the key word option `SPECIFY` in Data Set 2B.

The input format for specifying keyword (character) variable `SPECIFY` has changed. This character variable is now specified within the `OPTIONS` block that is now specified between Data Set 0 and Data Set 1. A new character variable option was added that allows users to specify pumping rates using separate tabular input files for each well. Each tabular input file consists of a series of simulation times and pumping rates. The applied pumping rate will be interpolated from the tabular input file using the times at the end and beginning of the time step. Options must be preceded with the "OPTIONS" specification and followed by the "END" specification. Characters can be specified as upper or lower case.

#### Optional character variables for WELL in any order:

```
OPTIONS  
[SPECIFY PHIRAMP IUNITRAMP]  
[TABFILES NUMTAB MAXVAL]  
END
```

Definitions for new character variable option:

**TABFILES** -- An optional character variable. When **TABFILES** is specified, all pumping rates for all wells in the model will be input using separate time series tabular input files.

**NUMTAB** -- An integer variable that is the number of tabular input files that will be read for interpolating pumping rates for each well in the model. A separate tabular input file is required for each well in the model. Wells can be made inactive by specifying pumping rates of zero for times when a well is inactive.

**MAXVAL** -- An integer value equal to the maximum number of time-series values specified in the tabular input file, not including header lines. Tabular input files each can have a different number of values and **MAXVAL** is the number of lines in the tabular input file that has the most lines as compared to all other tabular input files.

IF **TABFILES** is specified, then DATA SET 6 is replaced with the following **NUMTAB** lines for stress period 1 only. DATA SET 6 is not required for stress periods following the first stress period when the **TABFILES** option is used.

[**TABUNIT TABVAL TABLAY TABROW TABCOL**] #repeat this line **NUMTAB** times for stress period 1.

**TABUNIT** -- An integer value equal to the unit number for the tabular input file. This unit number must match the unit number specified in the MODFLOW Name file as type data.

**TABVAL** -- An integer value equal to the number of lines in this tabular input file not including header lines.

**TABLAY** -- An integer value equal to the MODFLOW layer for the cell to which the pumping rates will be applied.

**TABROW** -- An integer value equal to the MODFLOW row for the cell to which the pumping rates will be applied.

**TABCOL** -- An integer value equal to the MODFLOW column for the cell to which the pumping rates will be applied.

Multi-Node Well (MNW2) Package:

(1) A bug was fixed to correct budget calculations when the UPW Package is used with MNW2. The model stopped and an error was reported when a well was screened in multiple cells and one of the cells was inactive. This error was changed to be a warning (and execution continues) if one of the screened cells is active. (2) A floating-point exception was fixed.



## Surface Water Routing (SWR) Process

The names of the source files were changed from `gwf2swr7_NWT.f` to `gwf2swr7.f` and `gsol7.f` to `gwf2swr7util.f`.

### C. GSFLOW Modules

Changes to the GSFLOW Modules are:

`gsflow_prms` module:

- Print **var\_init\_file** and **var\_save\_file** to screen if used.
- Print simulation time period to screen.

`gsflow_sum` and `gsflow_budget` modules:

- Updated some variable names and some computations to be compatible with new water-balance spreadsheet utility.

### Version, 1.2.0 08/01/2015:

This version of GSFLOW is based on MODFLOW-NWT version 1.0.9, MODFLOW-2005 version 1.11.0, and PRMS version 4.0.1. Substantial enhancements were added for this version of the software, in particular the inclusion of a restart capability for GSFLOW (Regan and others, 2015) and the integration of several (but not all) of the new PRMS-IV modules documented by Markstrom and others (2015). The restart capability is fully documented in Regan and others (2015); no additional information about the capability is included in these release notes. Those PRMS-IV modules that have been included with this version of GSFLOW are identified above in the 'PRMS Modules' functionality list. All of the new modules are described in detail by Markstrom and others (2015). Some input and output options are not available in the current GSFLOW release, such as those related to the `strmflow_lake` module.

In addition to the major enhancements, a number of bug fixes and slight modifications have been made to the software; those bug fixes and modifications that are more than simply cosmetic are described below, beginning with changes to the PRMS Modules and then progressing to changes to the MODFLOW Packages and GSFLOW Modules.

### PRMS Modules

The PRMS version (4.0.1) included in GSFLOW version 1.2 is based on PRMS-IV as documented in Markstrom and others (2015), with the addition of the flexible-dimension option (described below) and new modules and parameters; minor bug fixes; additional checks for valid input values; and general code clean-up. Code clean-up was done with the following objectives: (a) to reduce mixed floating-point computations by changing some variables to double precision (and

some to single precision) and using FORTRAN intrinsic functions to convert variables prior to mixed-precision computations—this change might produce slight changes to results for associated computations; (b) to reduce HRU based loops; and (c) to increase consistency of screen output. Note: for large models, users can reduce the size of the input Parameter Files by not including parameters for which the PRMS-assigned default values represent the needs of the application. A message is printed to the screen for each parameter that is used in a simulation at its default value and is not specified in the Parameter File. For example, if the default value of **carea\_max**, which is 0.6, is the value needed for all HRUs, that parameter does not need to be specified in the Parameter File.

Detailed descriptions of changes made for PRMS version 4.0.1 are described in the PRMS release notes included with the PRMS distribution ([http://wwwbrr.cr.usgs.gov/projects/SW\\_MoWS/PRMS.html](http://wwwbrr.cr.usgs.gov/projects/SW_MoWS/PRMS.html)). Changes in the specification of user inputs are reported as updates to tables in the Users' Manual (tables 2, 1-2, 1-3, and 1-5). The following sections highlight some of the more important changes.

### **General Updates and Enhancements**

- **Flexible dimension option**: Previously, parameters had only one option for the number of values [that is, the dimension(s)] specified in the Parameter File. Now, many parameters can be specified using the original dimension(s) or using compatible dimensions up to a maximum number of values based on the specified dimension(s). For example, some parameters had a maximum dimension of **nmonths** and now have a maximum dimension of **nhru,nmonths**. Possible dimensions for a parameter with a maximum dimension of **nhru,nmonths** are **one**, **nmonths**, **nsub**, **nsub**, **nmonths**, **nhru**, and **nhru,nmonths**. Possible dimensions for a parameter with a maximum dimension of **nhru** are **one**, **nsub**, and **nhru**. Possible dimensions for a parameter with a maximum dimension of **nssr** are **one**, **nsub**, and **nssr**. Possible dimensions for a parameter with a maximum dimension of **ngw** are **one**, **nsub**, and **ngw**. GSFLOW will read the dimension and number of values and load the parameter array used in the model to the maximum dimension. Thus, the user has several options to specify the number of parameter values based on the spatial and temporal variability of the parameter, available data, or some other modeling purpose. As the number of HRUs is increased, the specified parameter values to the maximum dimension the amount of memory used for an execution will be greater by the memory difference between the original maximum number values and new maximum number of values. The maximum number of values for most parameters has not changed. Maximum parameter dimensions are identified in PRMS-IV updated tables 1-1 and 1-3 ([ftp://brrftp.cr.usgs.gov/pub/mows/software/prms/4.0.1/PRMS\\_tableUpdates\\_4.0.1.pdf](ftp://brrftp.cr.usgs.gov/pub/mows/software/prms/4.0.1/PRMS_tableUpdates_4.0.1.pdf)).

The flexible dimension option was added to accommodate simulation of large model domains that require increased spatial and/or temporal distribution of parameter values. Additionally, the number of lines in Parameter Files can be significantly reduced by specifying a single (dimension **one**) or **nsub** values for parameters that have a constant value for all HRUs or subbasins. This capability may change results when dimensions are specified to be greater than the original dimension(s). If the parameter dimensions are not

changed, results should be the same. However, some computations in the `ddsolrad` and `ccsolrad` modules are based on variables for each HRU rather than basin-wide variables, so the potential solar radiation (variable `swrad`) can be significantly different than previous versions for large model domains.

An example of a parameter with a maximum number of values equal to `nhru` that might have the same value for all HRUs when specified as a regular grid is `hru_area`. In this case, the area of each HRU can be specified as:

```
####  
hru_area  
1  
one  
2  
90.0
```

- The short-hand method for specification of parameter values as described on pages 4-5 in the 'GSFLOW\_v1.1.3\_Updates.pdf' document included in the GSFLOW distribution is deprecated and no longer supported. While this option is available with this GSFLOW release, it is recommended that users do not use it and that they convert any existing models to use the flexible dimension option.
- Surface-Depression Storage: Simulation of surface-depression storage is supported with this version of GSFLOW. See Markstrom and others (2015) and Viger and others (2010) for a description of this option, as well as the updated PRMS-IV [tables 1-3 and 1-5](ftp://brrftp.cr.usgs.gov/pub/mows/software/prms/4.0.1/PRMS_tableUpdates_4.0.1.pdf) (ftp://brrftp.cr.usgs.gov/pub/mows/software/prms/4.0.1/PRMS\_tableUpdates\_4.0.1.pdf) for descriptions of all current surface-depression input and computed results.
- Restart option (or Use of Initial Conditions Files option): This option has been enhanced with bug fixes. Modules affected: `potet_pan`, `transp_tindex`, `temp_dist2`, `obs`, `gwflow`, `intcp`, `climateflow`, `temp_1sta`, `temp_laps`, `srunoff_smidx`, `srunoff_carea`, `snowcomp`, `soilzone`, `transp_tindex`, `basin_sum`, and `xyz_dist`. Restart code removed from `subbasin` module.
- Solar Radiation and ET: Modifications made to the solar-radiation modules described on page 15 may lead to noticeable changes in simulation results for areally extensive basins in which there are large contrasts in topographic relief throughout the basin. For example, the modifications led to changes in simulated results for the Sagehen GSFLOW model distributed with the release because of the large relief in the basin and presence of north- and south-facing slopes.

### New Modules and Utility Routines

- Several new PRMS modules have been added for this GSFLOW release (`ide_dist`, `potet_hs`, `potet_pt`, `potet_pm`, `transp_frost`, `frost_date`, `muskingum`, and

`strmflow_in_out`). See the PRMS-IV documentation manual for complete descriptions of these modules and online [table 2](#) for brief descriptions of each module (as well as table 1 in “GSFLOW\_Input\_Instructions.pdf”).

- `nhru_summary` module: Output CSV files of user-selected output variables (see ‘nhru\_summary.pdf’ in the “doc\Related reports” subdirectory of the GSFLOW distribution file.
- `routing`: A utility routine to compute segment variables used with stream-routing modules `muskingum` and `strmflow_in_out`. Most code for this routine was originally in the `muskingum` module.
- `prms_time`: A utility routine to set time-related variables for each time step that are used by most other modules. Most code was originally in the `obs` module.
- `water_balance`: A utility routine to compute debug water budgets for the major hydrologic processes when control parameter **print\_debug** is specified equal to 1. Code for this utility was originally in modules `intcp`, `soilzone`, `srunoff_smidx`, `srunoff_carea`, `snowcomp`, and `gwflow`.

## **New Parameters**

### **New Parameters Specified in the Control File**

- **parameter\_check\_flag**: A 0 value means perform parameter-range checks on a number of parameters, such as **soil\_moist\_max**, **soil\_rechr\_max**, **smidx\_coef**, **smidx\_exp**, **covden\_win**, **covden\_sum**, and **hru\_aspect**, and to treat some of those parameter-range checks as WARNINGS, as done for most parameters in previous versions; if specified as 1, these checks are treated as ERRORS; if specified as 2, the parameters are checked and then the simulation stops, even if no ERRORS are found; default value = 1. Modules affected: `potet_jh`, `precip_dist2`, `precip_laps`, `soilzone`, `soltab`, `srunoff_smidx`, and `srunoff_carea`. It is recommended that a value of 1 be used for initial simulations so that possible parameter specifications are within valid ranges.
- **cbh\_check\_flag**: A 0 value means do not check values in CBH file; 1 means to check for invalid values (for example, less than lower bound or greater than upper bound), reading past the end of file during a simulation, and non-sequential time series, such as not having the correct number of days in each year; default value = 1. Specifying **cbh\_check\_flag** equal to 0 should only be done after the CBH file(s) are verified using **cbh\_check\_flag** specified equal to 1. Setting **cbh\_check\_flag** equal to 0 can reduce execution time.
- **cbh\_binary\_flag**: A 0 value means all CBH Files are text files, the only option in previous versions; 1 means all CBH files are in binary format and generated using the same input order of values as would be done for a text CBH File.
- **humidity\_cbh\_flag**: Flag to specify to read a CBH File with humidity values (0=no; 1=yes; default = 0).
- **humidity\_day**: File name of the humidity CBH file; this can be a full or relative path.

- **windspeed\_cbh\_flag**: Flag to specify to read a CBH file with wind-speed values (0=no; 1=yes; default = 0).
- **windspeed\_day**: File name of the wind-speed CBH file; this can be a full or relative path.
- **print\_debug**: New option added: specifying a -1 value minimizes warning messages and other messages printed to the screen during a simulation, such as the current stress period and time step and when values of parameter **soil\_rechr\_max** is specified greater than **soil\_moist\_max**. This can reduce execution time.

#### New Parameters and Dimensions Specified in the Parameter File(s)

- **potet\_cbh\_adj(nhru,nmonths)**: Calibration coefficient for values specified in a **potet\_day** CBH file; valid range 0.5 to 1.5; default value = 1.0.
- **snowpack\_init(nhru)**: Initial snowpack-water equivalent, in inches; valid range 0.0 to 500.0; default value = 0.0.
- **tmax\_allrain\_sta(nrain,nmonths)**: Monthly (January to December) maximum air temperature when precipitation is assumed to be all rain; if the maximum air temperature at a precipitation-measurement station is greater than or equal to this value, then precipitation is assumed to be all rain; default value = 38.0. Parameter **tmax\_allrain(nhru,nmonths)** is used to determine the form of values distributed to HRUs. Specified for module *ide\_dist*.
- **tmax\_allsnow\_sta(nrain,nmonths)**: Monthly (January to December) maximum air temperature when precipitation is assumed to be all snow; if the maximum air temperature at a precipitation-measurement station is less than or equal to this value, then precipitation is assumed to be all snow; default value = 32.0. Parameter **tmax\_allsnow(nhru,nmonths)** is used to determine the form of precipitation values distributed to HRUs. Specified for module *ide\_dist*.
- **tmax\_allrain\_dist(nmonths)**: Maximum air temperature when parameter **adjust\_snow(nhru,nmonths)** is used precipitation adjustment assumed to be all rain; if the computed HRU maximum air temperature is greater than or equal to this value, precipitation is all rain, default = 38.0. Parameter **tmax\_allrain(nhru,nmonths)** is used to determine the form of precipitation values distributed to HRUs. For exiting models, users need to add parameter **tmax\_allrain\_dist** as a copy of the existing parameter **tmax\_allrain**. Both parameters are required for models using module *xyz\_dist*.
- **tmax\_allsnow\_dist(nmonths)**: Maximum air temperature when precipitation is assumed to be all snow; if the computed HRU maximum air temperature is less than or equal to this value, precipitation is all snow, default = 32.0. Parameter **tmax\_allsnow(nhru,nmonths)**: Maximum air temperature when precipitation is assumed to be all rain; is used to determine the form of values distributed to HRUs. Parameter **tmax\_allsnow(nhru,nmonths)** is used to determine the form of precipitation values distributed to HRUs. For existing models, users need to add parameter **tmax\_allsnow\_dist** as a copy of the existing parameter **tmax\_allsnow**. Both parameters are required for models using module *xyz\_dist*.

## Parameters and Variables Removed

See the PRMS-IV updated [tables](#)

([ftp://brrftp.cr.usgs.gov/pub/mows/software/prms/4.0.1/PRMS\\_tableUpdates\\_4.0.1.pdf](ftp://brrftp.cr.usgs.gov/pub/mows/software/prms/4.0.1/PRMS_tableUpdates_4.0.1.pdf)) for descriptions of these parameters.

### Parameters Specified in the Control File

- **soilzone\_module**: Not needed because the `soilzone` module is always active.

### Parameters and Dimensions Specified in Parameter Files

- **adj\_by\_hru**, **rain\_sub\_adj**, and **snow\_sub\_adj** parameters that were specified for module `climate_hru` are unnecessary because parameters **rain\_adj** and **snow\_adj** can have the dimensions (**nsub,nmonths**) due to the new flexible in the dimension capability; thus, when using `climate_hru` for the precipitation distribution module use **rain\_adj(nsub,nmonths)** and **snow\_adj(nsub,nmonths)** to replace **rain\_sub\_adj** and **snow\_sub\_adj**.
- **hru\_ssres**, **ssr\_gwres**, and **hru\_gwres** parameters are not needed as **nhru** must equal **nssr** and **ngw**.
- **basin\_area** parameter is not needed as it is computed based on **hru\_area**.
- **nform**: this dimension removed as it is not used.
- **form\_data**: this input variable removed as it is not used.
- **snow**: input variable named changed to **snowdepth** to be more explicit about its meaning.

## Screen Output Changes

- Increased consistency of screen output for module descriptions, HRU identification numbers, and dates.
- When module `climate_hru` is active for more than one type of CBH file, the module description is printed for each climate type. For example, if `climate_hru` is used to input temperature and precipitation values, a line is printed with the `climate_hru` version identification for the active Temperature Distribution and Precipitation Distribution modules. Previously, the identification was printed once no matter how many climate types were input using `climate_hru`.

## Changes by Process

### Input Data

`climate_hru` module:

- Allows CBH Files to be input in binary format when control parameter **cbh\_binary\_flag** is specified equal to 1.
- Values for CHB Files are not checked for having valid values unless control parameter **cbh\_check\_flag** is specified equal to 1 (default value); setting this parameter to 0 can reduce execution time.

- Humidity and wind speed CBH Files can be input, which are needed for new module `potet_pm`.
- Parameters to adjust precipitation by subbasin are no longer used because parameters **`snow_cbh_adj`** and **`rain_cbh_adj`** can be dimensioned (**`nsub,nmonths`**) using the flexible dimension option. Thus, models that used the subbasin specification need to be updated to remove parameters **`adj_by_hru`** and **`hru_subbasin`** and names for parameters **`snow_sub_adj`** and **`rain_sub_adj`** changed to **`snow_cbh_adj`** and **`rain_cbh_adj`**, respectively.
- Values in potential evapotranspiration CBH Files can be adjusted using new parameter **`potet_cbh_adj`**.

#### obs module:

- Removed dimension **`nform`** and variable `form_data` because they are not used, users need to remove both of these if they are specified in a Data File.
- Variable named `snow` changed to `snowdepth`. Users need to make this change if snow depth is specified in a Data File.
- Code related to time step moved to new `prms_time` utility routines.
- Values in Data File no longer checked for NaN values. This can reduce execution time.

#### Climate

- Parameters used in equations optionally can use two-dimensional arrays (**`nhru,nmonths`**) to add spatial variation for large models. However, this change is backward compatible with existing models. Modules affected: `precip_1sta`, `precip_laps`, `precip_dist2`, `xyz_dist`, and `climate_hru` (parameters **`tmax_allrain`**, **`tmax_allsnow`**, **`adjmix_rain`**); `temp_1sta`, `temp_laps`, and `xyz_dist` (parameters **`tmax_adj(nhru,nmonths)`**, **`tmin_adj(nhru,nmonths)`**); `temp_1sta` (parameters **`tmax_lapse(nhru,nmonths)`** and **`tmin_lapse(nhru,nmonths)`**).
- Small values (< 1.0E-05) of input precipitation are not ignored. This was done because in some cases—such as with output from General Circulation Models—computed precipitation could include small values. Modules affected: `precip_1sta`, `precip_laps`, `climate_hru`, and `xyz_dist`.
- Added error check for computed values of `tmin > tmax` when determining form of precipitation. Modules affected: `climate_hru`, `ide_dist`, `precip_1sta`, `precip_laps`, and `xyz_dist`.
- Modules `temp_1sta` and `temp_laps`: the initial value used to replace a missing value was changed from 50.0 to the value of **`tmax_allrain(start_month)`**; this only affects the first-time step. **Bug fix:** if too many missing values (greater than parameter **`max_missing`**) are found, an error message is printed and the execution stops, instead of continuing.
- Modules `xyz_dist` and `ide_dist`: values of measured precipitation as specified in the Data File were used in calculations that could change the original value; thus, if these values were output, they may not match the values specified in the Data File. Now the

modules use new arrays that are originally set to the measured values and allowed to be modified in computations, but not affect input values.

- Module `xyz_dist`: error check added to be sure that at least two climate stations are in the Data File.
  - Parameters **adjust\_snow** and **adjust\_rain** have maximum dimensions (**nrain,nmonths**) because the adjustments are applied to measured precipitation from the Data File instead of (**nmonths**). This change does not affect existing models.
  - Added parameters **tmax\_allsnow\_dist** and **tmax\_allrain\_dist(nmonths)**; these are the used to determine the form of the measured precipitation specified in the Data File. For existing models, users need to add copies of **tmax\_allsnow** and **tmax\_allrain** to the Parameter File and then change the copies to have the parameter names **tmax\_allsnow\_dist** and **tmax\_allrain\_dist**. Thus, all four parameters must be specified. The **tmax\_allsnow** and **tmax\_allrain** parameters are used to determine the form of HRU distributed precipitation values and now have maximum dimensions (**nhru,nmonths**).

### Solar Radiation

ccsolrad and ddsolrad modules:

- Some solar radiation equations were dependent on basin-area weighted average and monthly varying parameter values. All computations are now computed based on parameters for each HRU. **This can lead to noticeable changes in results for larger basins.** For example, in the `ccsolrad` module, a single cloud cover fraction was computed for the current month based on a basin value for minimum and maximum temperature and monthly cloud cover parameter values. Now, the cloud cover fraction is computed based on the HRU daily minimum and maximum temperature and values of the cloud-cover parameters that can be specified for each HRU and month. Similarly, in module `ddsolrad` the degree-day and radiation adjustment values are computed for each HRU instead of as basin-wide values.
- `ddsolrad` module: **Bug fix:** if the computed radiation-adjustment factor based on parameters **dday\_slope** and **dday\_intcp** is greater than the value of parameter **radmax**, it is set to **radmax** rather than as computed. The check was added as a precaution and to be consistent with module `ccsolrad`.
- **Bug fix:** modules incorrectly assumed that the simulation time period was always winter for Southern Hemisphere applications. This meant that solar radiation adjustment values as specified by parameter **radj\_wppt** were always used for models located in the Southern Hemisphere; thus, values for parameter **radj\_sppt** were not used.
- **Bug fix:** check added to be sure at least one value of parameter **hru\_solsta** is specified greater than 0 when dimension **nsol** is specified greater than 0. If all values of **hru\_solsta** were specified equal to 0, an array would be referenced beyond its memory limit, which could produce errant results or cause the simulation to abort.

### Potential Evapotranspiration



- Module `potet_pan`: **Bug fix**: added check to be sure pan evaporation data are included in the Data File. Added check for values of parameter `hru_pansta` specified greater than dimension `nevap` or equal to 0. If either condition or no pan evaporation data are in the Data File, an error message(s) is printed, and execution stops.
- Module `potet_jh`: Added check for values of parameter `jh_coef_hru` specified greater than 150 or less than -50 and values of `jh_coef` specified greater than 10 or less than -1; if true, a warning message is printed when control parameter `parameter_check_flag` is specified equal to 0; else, an error message is printed and execution stops.

### Canopy

- Module `transp_tindex`: **Bug fix**: When the value of parameter `transp_end` equals the current month and the current day is the first day of the month, transpiration is turned off (variable `transp_on` is set to 0) and the related local variables, `transp_check` and `tmax_sum`, are set to 0. After this check, if the current month equals the value of parameter `transp_beg`, `transp_check` and `tmax_sum` are checked to determine if transpiration needs to be turned on if the value of `tmax_sum` is greater than the value of parameter `transp_tmax`. If true, variable `transp_on` is set to 1, `transp_check` is set to 1, and `tmax_sum` is set to 0. Previously, the checks were reversed, which could keep transpiration on for a few days in a month, depending on the value of `tmax_sum` when the values of `transp_beg` and `transp_end` were specified equal to each other.
- Parameters used in equations optionally can use two-dimensional arrays (`nhru,nmonths`) or one-dimensional arrays (`nhru`) to add spatial variation for large models. However, this change is backward compatible with existing models. Modules affected: `intcp` (parameters `epan_coef(nhru,nmonths)` and `potet_sublim(nhru)`).
- Module `intcp`: snow interception on an HRU is computed based on any precipitation on the HRU rather than also in the basin. Previously, snow interception in the canopy was not computed on HRUs if precipitation occurred anywhere in the basin. **This could lead to noticeable change in results for large models**, but, may not affect results for small basins.

### Cascades

- Code related to cascading flow in stream segments and lakes removed. Cascade variables related to groundwater cascades changed to double precision.
- Two groundwater cascade arrays were initialized `ngw` number of times instead of once. This fix slightly reduces execution time for PRMS-only simulations.
- Tolerance used to check for the fraction leaving an HRU or GWR adding up to exactly 1.0 was changed from 1.00001 to 1.001. If this check finds an issue, the cascade links are adjusted.

### Snow Dynamics (module `snowcomp`)

- Added check to be sure values of `snowcov_area` are not equal to zero when a snowpack exists. This would be very rare and only possible when the first value of a snow-depletion curve was specified equal to zero.

- Checks were added to be sure *pkwater\_equiv* is set to 0.0 if it is computed as negative. For example, there was the possibility that the snowpack water equivalent was computed as a value < 0 when the amount of free water in the snowpack was less than the computed amount of free water that the snowpack could hold. Though this condition is likely very rare, it could have resulted in **very slight differences** in results in the value of variables *pkwater\_equiv*, *pk\_depth*, and *snowmelt*.
- **Bug fix:** Computation of snowpack density and snowpack depth are computed based on a finite-difference approximation, which produced slightly incorrect results for days when new snow falls when a snowpack does not exist. This bug could produce significant errors when the new snowfall is large compared to the existing snowpack.
- Canopy density on each HRU for each time step is used in computations instead of only values of parameter **covden\_win**. This could result in **noticeable changes in results** when snow falls on a day during the transpiration period (growing season) and the value of **covden\_sum** is significantly different than the value of **covden\_win** for an HRU.
- If values for parameters **den\_init** and/or **den\_max** are specified less than 1.0E-06, they are set to 1.0E-06 instead of 0.1 and 0.6, respectively.
- **Bug fix:** If values of **cov\_type** were specified equal to 4 (coniferous), the computed convection-condensation value that is based on parameter **cecn\_coef** was not reduced by half as it should for all tree types. Specifying **cov\_type** equal 4 is not fully implemented and is treated the same as **cov\_type** equal 3. Few models are believed to have used **cov\_type** equal 4; those that did could see differences in results related to the snowpack.

#### Surface Runoff (modules *srunoff smidx* and *srunoff carea*)

- Added check for values of parameter **carea\_max** specified greater than 1.0; if true, an error message is printed, and execution stops.
- Added check for the computation of the maximum contributing area for module *srunoff\_smidx* based on the values of parameters **smidx\_coef**, **smidx\_exp**, and **soil\_moist\_max**. If the maximum contributing area for any HRU is greater than 2.0, a warning message is printed if control parameter **parameter\_check\_flag** specified equal to 1. When this condition is true, it indicates that the values of **smidx\_coef** and **smidx\_exp** can be insensitive as compared to the values of **carea\_max**, thus increasing values of **smidx\_coef** or **smidx\_exp** could have no effect on computed results.

#### Soilzone Processes (module *soilzone*)

- Error check added for interflow computation for the equation  $\text{SQRT}(\text{coef\_lin}^{**2.0} + 4.0 * \text{coef\_sq} * \text{ssres\_in}) = 0.0$ ; if true, a divide by 0 would have occurred; this would have been a very rare condition if ever.
- **Bug fix:** Corrected setting of variable *soil\_zone\_max* to account for parameter **soil\_moist\_max** only being applicable to the pervious area of each HRU. This does not affect other soilzone computations, just the values of variables *soil\_zone\_max* and *soil\_moist\_frac*, which are computed results that are not used in other computations.

- Water-balance check when control parameter **print\_debug** = 1 was incorrect when swale HRUs are present because the computed evaporation from swale HRUs was not included in the water-balance equation.
- Added checks for computed infiltration less than 0.0 and computed interflow coefficient equal to 0.0; these conditions would not likely occur.
- Can remove from the Parameter File parameter **gvr\_hru\_id** when dimensions **nhru** equals **nhru cell**.

#### Groundwater flow (module `gwflow`)

- Values of parameter **gwflow\_coef** that are specified greater than 1.0 are now allowed; a warning is issued in this case.
- **Bug fix:** Any water added due to specified values of parameter **gwstor\_min** was incorrectly added twice.
- Warning checks of some parameters used incorrect array index; thus, the value printed was incorrect.
- If any HRUs were specified as inactive, then the parameter values of all remaining HRUs were not checked for being valid values.

#### Output Reports (modules `basin_sum` and `map_results`)

- Module `map_results`: (a) Added option to output daily mapped results (parameter **mapvars\_freq** specified equal to 7). (b) Notes: the units of output variables are equal to the units of the variable for **mapvars\_units** specified equal to 0. Units for variables could be, for example, inches, inches/day, degrees Fahrenheit, and degrees Celsius. However, when the **mapvars\_units** value is specified greater than 0, the units of all selected **map\_results** output variables as specified by control parameter **mapOutVar\_names** must have units of either inches or inches/day, because the code only converts inches to a metric unit. (c) **Bug fix:** if parameter **mapvars\_freq** was specified equal to 4 the yearly results were not computed.
- Module `basin_sum`: Water-balance computations did not include water in stream segments when using the `muskingum` module or surface-depression storage computations. Water-balance computations are only computed when control parameter **print\_debug** is set to 1.
- **Bug fix:** Previous versions used variable `basin_stflow_in` instead of `basin_stflow_out` to set the basin-outflow variable `basin_cfs`; this bug only occurred when the `muskingum` module was active.
- Can remove from the Parameter File parameters **gvr\_hru\_id**, **gvr\_cell\_id** and **gvr\_cell\_pct** when dimensions **nhru** equals **nhru cell**.

#### **MODFLOW Packages**

GSFLOW version 1.2.0 is based on MODFLOW-NWT version 1.0.9, as well as updates that have been made to MODFLOW-2005 version 1.11.0. Since the last GSFLOW release (version 1.1.6) there have been two MODFLOW-NWT releases (versions 1.0.8 and 1.0.9) and two MODFLOW-2005 releases (versions 1.10.00 and 1.11.0). Changes made to MODFLOW-NWT and MODFLOW-2005 are described in the release notes for those codes; users are encouraged to review those release notes in addition to the notes provided below.

#### Specific notes on the MODFLOW Packages:

1. Although the current release versions of MODFLOW-NWT (1.0.9) and MODFLOW-2005 (1.11.0) include the Seawater Intrusion (SWI2) Package, GSFLOW version 1.2 does not. Other Packages that are distributed with MODFLOW-NWT and MODFLOW-2005 that are not a part of GSFLOW (as described in the original GSFLOW documentation by Markstrom and others, 2008) are the RCH, EVT, ETS, IBS, SUB, DRT, RIV, DRN, and RES Packages, as well as the STR, SWR (MODFLOW-NWT only), SWT, LMT, SWI, and HYDMOD Packages and capabilities. The PCGN Solution Package also was removed for this version of GSFLOW.
2. Changes made to MODFLOW-NWT since the version 1.0.9 release are the following: (a) a minor bug was fixed that relates to simulating unsaturated-zone flow beneath lakes; (b) some variables in the SFR2 Package were initialized; and (c) some variables in the UZF Package for calculating runoff were initialized.
3. Multi-Node Well (MNW2) Package: A bug was fixed to correct budget calculations when the UPW Package was used with MNW2.

#### GSFLOW Modules

Changes to the GSFLOW Modules are:

1. Previous versions of GSFLOW required that a PRMS Parameter File be specified in the Control File for a MODFLOW-only simulation. The code has been updated so that the user no longer needs to specify a PRMS Parameter File for a MODFLOW-only simulation. Thus, for a MODFLOW-only simulation, the Control File could be as short as the following example for the Sagehen Creek GSFLOW model distributed with the software:

```
Control File for a MODFLOW-only simulation, Sagehen Creek Watershed
####
model_mode
1
4
MODFLOW
####
modflow_name
1
4
../input/modflow/sagehen.mf.nam
```

Note, however, that for restart simulations, the user also will need to specify control parameters **modflow\_time\_zero**, **start\_time**, and **end\_time**.

2. A bug was discovered in the conversion of time units from MODFLOW to GSFLOW units. Previous versions of the code assumed that all MODFLOW time units were in days. MODFLOW models that used units other than days resulted in incorrect GSFLOW results. The code was changed to allow time units other than days to be used for MODFLOW input, as defined through variable ITMUNI that is specified within the Discretization (DIS) file. The bug required modifications be made to the `gsflow_budget`, `gsflow_sum`, `gsflow_prms2mf`, and `gsflow_mf2prms` modules.

3. Another small change was made in the calculation of change in storage for all lakes used for printing the budget to the overall GSFLOW budget. This change had a small effect on values of lake-storage change printed to the CSV and GSFLOW budget files.

4. Code was added to the `gsflow_prms` module to check for deprecated-module names. If these names are found, a warning message is printed. To maintain compatibility with previous versions of the software, the deprecated-module name is set to the current name.

#### **Version 1.1.6 03/20/2013:**

This version of GSFLOW is based on MODFLOW-2005 version 1.9.01, MODFLOW-NWT version 1.0.7, and PRMS version 3.0.5. A number of enhancements and bug fixes have been done for this release. All of the updates are described in file "GSFLOW\_v1.1.6\_Updates.pdf."

#### **Version 1.1.5 01/15/2012:**

This version of GSFLOW is based on MODFLOW-2005 version 1.8, MODFLOW-NWT version 1.0.3, and PRMS version 3.4179. Several enhancements and bug fixes have been done for this release. Important enhancements include addition of the Newton Formulation for MODFLOW and the Map Results and Climate by HRU Distribution Modules for PRMS. All of the updates are described in the files "GSFLOW\_v1.1.5\_Updates.pdf," "Map\_results.pdf," "Climate\_hru.pdf," "Appendix1\_Tables\_v1.1.5.pdf," and "SFR2\_for\_GSFLOW\_v1.1.5.pdf."

#### **Version 1.1.4 06/01/2011:**

This version of GSFLOW is based on MODFLOW-2005 version 1.8 and PRMS version 2.3116. Users are encouraged to review the release materials for MODFLOW-2005 for a full description of updates made for version 1.8.

A number of changes and bug fixes were made for this release. The modifications are grouped by PRMS modules and MODFLOW Packages.

### **PRMS Modules:**

Potential Solar Radiation Module (*soltab\_hru\_prms.f*): The area-weighted mean basin latitude was computed incorrectly for models having inactive cells. This bug affected the computation of potential solar radiation on a horizontal plane for the basin latitude and snow computations involving solar radiation.

Cascading-Flow Module (*cascade\_prms.f*): The default values for **hru\_down\_id** and **gw\_down\_id** were changed from 1 to 0. If an HRU is determined to be a swale, an error message is issued, and the simulation stops if the value of **hru\_type** is not specified with the value 3.

Ground-Water Reservoir Module (*gwflow\_casc\_prms.f*): Units for variables *gw\_in\_ssr*, *gw\_in\_soil*, and *gwres\_in* were computed in units of inches. They are now computed in units of acre-inches, as documented.

Surface-Runoff and Infiltration Modules (*srunoff\_smidx\_casc.f* and *srunoff\_carea\_casc.f*): Evaporation from impervious areas of HRUs is now computed at the potential evapotranspiration rate rather than at the rate of unsatisfied potential evapotranspiration. Also, a check was added to *srunoff\_carea\_casc.f* to be sure the computed contributing area used to compute surface runoff does not exceed 1.0. This check is made for each HRU for each time step.

Lapse-Station Temperature-Distribution Module (*temp\_laps\_prms.f*): If the altitudes of the temperature-measurement stations used to compute lapse rates are equal, the code sets the difference to 1.0 in units based on the value of **elev\_units**. This was done to avoid divide by zero.

Precipitation-Distribution Modules (*precip\_prms.f*, *precip\_laps\_prms.f*, *precip\_dist2\_prms*, *xyz\_dist.f*): If the computed maximum and minimum air temperatures are equal, the difference is set to 0.01 degrees Fahrenheit. Also, for module *precip\_laps\_prms.f*, if the altitudes of precipitation measurement stations used to compute lapse rates are equal, the code sets the difference to 1.0 in units based on the value of **elev\_units**. This was done to avoid divide by zero.

### **MODFLOW Packages:**

Lake Package (*gwf2lak7.f*): Corrected two bugs. The first caused the package to incorrectly set the uppermost active cell beneath a lake cell to **NLAY**. The second occurred in the calculation of outflow to a stream for specified outflow diversions; the lake stage was not being set correctly.

Unsaturated-Flow Package (gwf2uzf1.f and gwfuuzmodule.f): Added deallocate statements for the variables **CHECKTIME**, **MORE** and **LAYNUM**. The default value for the variable **SURFDEP** was changed from 1.0 to 1.0x10-6.

Streamflow-Routing Package (gwf2sfr7.f and gwfsfrmodule.f): Modifications were made to correct the effects of lakes inundating stream cells. Seepage in inundated stream cells was not being set to zero in the budget routine.

### **Version 1.1.3 03/01/2011:**

This version of GSFLOW is based on MODFLOW-2005 version 1.8. Users are encouraged to review the release materials for MODFLOW-2005 for a full description of updates made for version 1.8. This version of GSFLOW includes (1) the new Grid Report Module, (2) enhanced input options for the PRMS Parameter File, (3) a new option for the SFR2 Package to specify streamflows to simulated stream segments in tabular files that are external to the SFR2 main input file, and (4) several other smaller modifications and enhancements. All of the updates are described in the file 'GSFLOW\_v1.1.3\_Updates.pdf' provided in the .\doc\GSFLOW subdirectory. Revised input instructions for the SFR2 Package (for use with GSFLOW) are provided in file 'SFR2\_for\_GSFLOW\_v1.1.3.pdf' in the same directory. The Appendix 1 tables ('Appendix1\_Tables\_v1.1.3.pdf') also have been updated for the new Grid Report Module. Users are encouraged to review the updated documents.

### **Version 1.1.2 07/23/2010:**

This version of GSFLOW is based on MODFLOW-2005 version 1.8. Users are encouraged to review the release materials for MODFLOW-2005 for a full description of updates made for version 1.8.

#### Documentation Issues:

1. A new version of PRMSmanual.pdf was added to the 'doc' subdirectory to replace the previous, corrupted version.
2. An updated version of Appendix1\_Tables\_v1.1.pdf has been added to the 'doc\GSFLOW' subdirectory with the following changes:
  - a. Table A1-19 (Soil-Zone Module): parameters **ssr2gw\_exp**, **ssr2gw\_rate**, and **ssstor\_init** can only have the dimension **nssr**. Thus, delete "or **nhrucell**" from the dimension column. Also, parameter **ssrmax\_coef** is no longer used and should be removed from Parameter Files. (Table A1-18 in the GSFLOW manual, USGS TM6-D1 should also be updated.)
  - b. Table A1-4: Dimensions one, nmonths, and ndays no longer need to be specified in a GSFLOW Parameter File. (Table A1-4 in USGS TM6-D1 should also be updated.)

Note on dimension parameters **nhru**, **nssr**, and **ngw**:

The three-dimension parameters **nhru**, **nssr**, and **ngw**, which are specified in the dimensions section of the PRMS Parameter File, must all be equal when running GSFLOW in either PRMS-only or GSFLOW modes. If the three parameters are not equal, a message will be written to the user's screen and the parameters will be set equal to one another by the code.

Unsaturated-Zone Flow Package (gwf2uzf1.f):

1. An enhancement was done to increase the internal check made by UZF of the ratio of *ROOTDEPTH* to the thickness of the cell from 0.90 to 0.99.
2. Fixed memory out-of-bounds bug for array *BOTM* when **IUZFBND** was specified as less than zero. This problem was fixed by taking the absolute value of **IUZFBND** when used to access arrays.

Cascade Module (cascade\_prms.f):

Added check to ignore any cascade links that have invalid values specified for parameters **hru\_up\_id** or **gw\_up\_id**, such as less than 1 or greater than dimension **nhru**.

Subbasin Computation Module (subbasin\_prms.f):

If the code is executed in GSFLOW mode, subbasin streamflow variables will not be calculated.

Precipitation- and Temperature-Distribution Modules

(precip\_dist2\_prms.f and temp\_dist2\_prms.f):

Added input-data check to be sure that at least one climate station has a valid value for both precipitation and air temperature for each time step (as specified in the Data File). If all values of precipitation and air temperature are invalid for a time step, such as might occur if all values are specified as missing, a message is printed to the user's screen and the simulation is terminated.

Soil-Zone Module (soilzone\_prms.f):

1. Added a variable that saves the current version-date of the module. This variable is written to the *gsflow.log* file.
2. Enhanced debug option: If *print\_debug*, which is specified in the GSFLOW Control File, is set to 7, messages related to inconsistencies in the soil-zone input parameters are written to the new file *soilzone\_prms.dbg* in the user's current directory. Previously, these warning messages were written to the user's screen.
3. Added check to determine if swale HRUs are generating water storage (ponding on the surface) in excess of three times the specified value of parameter **sat\_threshold**. If this is the case, a message is written to the *soilzone\_prms.dbg* file if *print\_debug* has been specified as 7. It is recommended that users set **print\_debug** to 7 for initial GSFLOW simulations, and that the *soilzone\_dbg* file be examined to identify any parameter inconsistencies or potential problems with swale discretization prior to calibrating a model.

GSFLOW Computation-Control Module (gsflow\_prms.f):



Added a variable that saves the current version date of the module. This variable is written to the `gsflow.log` file.

GSFLOW Conversion Factors Module (`gsflow_setconv.f`):

Bug fix: Fixed possible use of incorrect index for arrays *Gwc\_row* and *Gwc\_col*.

GSFLOW Integration Module (`gsflow_prms2mf.f`):

1. Added input-data check to be sure that if an HRU is specified as a lake, the associated MODFLOW lake id is specified other than 0 for parameter **lake\_hru\_id**. If an error is detected, an error message is printed to the user's screen and model execution is terminated.
2. Corrected the computation of the number of soilzone computations per time step, which is printed in tabular form to the `gsflow.log` file.
3. Fixed a bug that caused the possible override of computed flows in transient GSFLOW simulations with flows specified in MODFLOW input files. Any specified flows in the MODFLOW input files are used in steady-state mode and ignored in transient mode of a GSFLOW simulation.

GSFLOW Summary Module (`gsflow_sum.f`):

Fixed the values reported for total basin precipitation and evaporation to include lake precipitation and evaporation.

### **Version 1.1.1 02/12/2010:**

This version of GSFLOW is based on MODFLOW-2005 version 1.8, which includes the Multi-Node Well version 2 Package. Additional minor changes also were made to version 1.8 that are explained in the MODFLOW-2005 release documents.

Added module `transp_index_prms`: This module is used to determine the active period of plant transpiration. The module is based on code previously located in the `potet_jh_prms`, `potet_hamon_hru_prms`, and `potet_pan_prms` modules. Therefore, those modules were changed as well.

Module `snowcomp_prms`:

1. A new output variable has been added:  
*basin\_snowdepth*, which is the basin area-weighted average snow depth.

Module `soilzone_prms`:

1. Three new output variables have been added:

*gw\_recharge\_day*, which is the sum of *soil\_to\_gw* and *ssr\_to\_gw* for each HRU for each daily time step

*gw\_recharge\_tot*, which is the sum of *soil\_to\_gw* and *ssr\_to\_gw* for each HRU for the total simulation time period

*basin\_gw\_recharge*, which is the basin area-weighted sum of *soil\_to\_gw* and *ssr\_to\_gw*

2. Parameter **ssrmax\_coef**, which is the maximum amount of gravity drainage to a PRMS groundwater reservoir or MODFLOW finite-difference cell, was set to a value of 1.0, the default value. Previously, the variable could range to a maximum value of 20.0, which was incorrect.

3. Added consistency checks to be sure the following parameters are not specified to a value less than zero: **soil\_moist\_max**, **soil\_moist\_init**, **soil\_rechr\_max**, **soil\_rechr\_init**, **ssstor\_init**, and **sat\_threshold**.

Module *gsflow\_prms2mf*:

1. Added parameter **mnsziter**, which is the minimum number of computations per time step that are computed by the Soil Zone Module. Computations within the Soil Zone Module include Dunnian runoff, interflow, changes in storage within the soil-zone reservoirs, components of evapotranspiration, and potential gravity drainage. The sequence of these computations is described in Table 9 of the GSFLOW documentation report (USGS Techniques and Methods 6-D1, p. 51). The following provides a more detailed explanation than is found in the GSFLOW manual of the conditions under which a GSFLOW time step concludes.

GSFLOW is based on an iterative-solution method in which convergence for each time step is ultimately dependent on whether or not changes in groundwater heads and flow rates meet closure criteria specified in the MODFLOW solver packages. If the MODFLOW convergence criteria are met, then GSFLOW continues to the next time step; if the convergence criteria are not met but the maximum number of MODFLOW iterations per time step is exceeded (as specified using variable **MXITER** or **ITMX** in the MODFLOW solver packages), then GSFLOW will print a warning message and continue to the next time step. Note that this differs from MODFLOW, in which MODFLOW stops if **MXITER** or **ITMX** are exceeded.

Convergence of groundwater heads and flow rates is dependent in part on the amount of gravity drainage that drains from the soil zone to the underlying unsaturated and saturated zones. The amount of gravity drainage is dependent on the potential gravity drainage computed by the Soil Zone Module and the vertical hydraulic conductivity and heads within the MODFLOW finite-difference cells. In many cases, heads and groundwater flow rates may converge faster if the amount of gravity drainage from the soil zone is no longer changing, which means that the MODFLOW computations will no longer be dependent on feedback from the Soil Zone Module.

Three GSFLOW input parameters are provided to allow the user to stop the soil-zone computations prior to convergence of the groundwater heads and flow rates. These parameters are (1) **szconverge**, which is the maximum allowed change in gravity drainage from the soil zone

for all HRUs between iterations required before the soil-zone computations cease; (2) **mnsziter**, which is defined above; and (3) **mxsziter**, which is the maximum number of computations per time step that are computed by the Soil Zone Module. Parameters **szconverge** and **mxsziter** have been available since the initial release of GSFLOW (see Table A1-25 in USGS Techniques and Methods 6-D1). Computations within the soil zone cease under three conditions listed in order of precedence: (1) the MODFLOW closure criteria are met or **MXITER** or **ITMX** is reached; (2) the maximum number of soil-zone computations is reached, as specified by parameter **mxsziter**; or (3) the maximum change in gravity drainage from the soil zone for all HRUs between iterations is less than the value specified for parameter **szconverge**. When conditions 2 or 3 are met, all computations done by the Soil Zone Module are held constant for the remainder of the current time step until MODFLOW-related convergence criteria are met (or **MXITER** or **ITMX** is exceeded). In addition, the amount of interflow and surface runoff to streams and lakes are held constant when soil-zone computations cease within a time step.

Previous versions of GSFLOW set the minimum number of soil-zone computations to 4, which is now the default value for **mnsziter**; **mnsziter** must be specified to be greater than 2. Specifying too small a value for **mxsziter** for complex GSFLOW models can stop soil-zone computations within a time step before the MODFLOW solution reaches a stable value; this may cause groundwater discharge from some finite-difference cells in subsequent iterations to be significantly different than that computed at the iteration in which the soil-zone computations ceased. In general, more complex models will require higher values of **mnsziter** and **mxsziter** than less complex models. Recent experience with GSFLOW indicates that (1) **mnsziter** and **mxsziter** should be set to values that equal the approximate average number and the maximum number, respectively, of MODFLOW iterations that are expected for any time step; and (2) that for some simulations, it may be advantageous to not limit the number of soil-zone computations by setting both **mnsziter** and **mxsziter** equal to **MXITER** or **ITMX** to allow for full feedback between PRMS and MODFLOW for each time step. The GSFLOW user may need to experiment with the values specified for **szconverge**, **mnsziter**, and **mxsziter** to be sure that the GSFLOW calculations have converged to stable values.

For the convenience of the user, the number of MODFLOW iterations and soil-zone computations are printed to the screen for the first day of each month and for each time step in the `gsflow.log` file. Also, if the number of iterations for a time step exceeds 75, the date and time of this time step is printed to the screen. At the end of a simulation, a summary table is printed to the screen and to the `gsflow.log` file giving the total and average number of MODFLOW iterations and soil-zone computations, as well as the total time the simulation took.

2. Bug fix: corrected do loop index of arrays used to check whether or not soilzone states are oscillating.

Module `gsflow_prms`:

1. Module `subbasin_prms` can now be called in both GSFLOW and PRMS-only modes. Previously, it could be called in PRMS-only mode. However, the user should be aware that some output variables written by the module are not relevant to a GSFLOW simulation, specifically

those related to the PRMS groundwater module: *sub\_inq*, *sub\_cfs*, *sub\_cms*, *sub\_gwflow*, and *subinc\_gwflow*. The *subbasin\_prms* module is useful in GSFLOW mode for computation of several subbasin states and fluxes, such as *sub\_interflow*, *sub\_precip*, *sub\_pkweqv*, *subinc\_interflow*, *subinc\_sroff*, *subinc\_precip*, *subinc\_snowmelt*, *subinc\_pkweqv*, *subinc\_actet*, *sub\_actet*, *sub\_sroff*, *sub\_snowmelt*, and *subinc\_snowcov*.

### **Version 1.1.00 11/18/2009:**

This version of GSFLOW is based on MODFLOW-2005 version 1.7. Added ability to specify inactive and swale hydrologic response unit types and the ability to calculate streamflow at internal basin nodes (the latter for PRMS-only simulations). Several additional bug fixes and minor enhancements were made for this release. All of the changes are described in the file 'GSFLOW\_v1.1\_Updates.pdf' located in the \doc\GSFLOW directory. Updated input formats for the PRMS and GSFLOW modules, including several new input parameters, are provided in the file 'Appendix1\_Tables\_v1.1.pdf,' which is also included in the \doc\GSFLOW directory. Also made changes to the Sagehen sample problem by simplifying the MODFLOW Name File and making the MODFLOW transient stress period consistent with the total number of time steps simulated by GSFLOW; these changes did not affect the results of the sample problem.

### **Version 1.0.00 03/05/2008:**

This version is the initial release.