GSFLOW Release Notes

Version 2.0.0 May 30, 2019

This file describes changes to GSFLOW with each official release. The most recent version of GSFLOW (2.0.0) is based on MODFLOW-NWT version 1.1.4, MODFLOW-2005 version 1.12.0, and PRMS version 5.0.0. GSFLOW can be used to run PRMS-only and MODFLOW-only simulations (that is, non-integrated simulations) in addition to the integrated GSFLOW mode. New functionality has been added: (a) all MODFLOW-NWT Packages are now available for MODFLOW-only mode; (b) input of PRMS dynamically-varying parameters and water use data for GSFLOW and PRMS-only modes and lakes simulation for PRMS-only mode; and (c) new PRMS output summary options have been added for stream segment (`nsegment_summary`), subbasins (`nsub_summary`), and model domain (`basin_summary`) variables that are similar to the `nhru_summary` module. See Regan and LaFontaine (2017) for documentation on the dynamic parameters, water-use, lake simulation, and `nhru_summary` options.

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Modules, file names, 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.

CONTENTS:

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 (such as measured or estimated precipitation, maximum and minimum air temperature, and optionally solar radiation and potential evapotranspiration), 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), PRMS-only, and MODFLOW-only. 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 (http://water.usgs.gov/ogw/gsflow/index.html).

SYSTEM REQUIREMENTS

GSFLOW is written in the Fortran 90 and C programming languages. The code has been used on personal computers running various forms of the Microsoft Windows operating system and Linux based 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.

Instructions for preparing input files for the current version of GSFLOW can be found in three resources; users are encouraged to review these resources when developing a GSFLOW model:

GSFLOW-specific instructions: The file 'GSFLOW_Input_Instructions.v.2.0.0.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.

PRMS Files: The file 'PRMS_tables_5.0.pdf' in the 'doc\Related reports (PRMS,MODFLOW,CRT)' subdirectory that provides updated tables for the PRMS-IV documentation report (Markstrom and others, 2015; http://pubs.usgs.gov/tm/6b7/) that describe PRMS modules, dimensions for parameters and variables, parameters in the Control File, parameters in the Parameter File, and input and output variables. Changes from PRMS version 4.0.3 are highlighted in <mark>yellow</mark> and <mark>green</mark>. See the file 'tm6b8_PRMS_enhancements.pdf' (Regan and LaFontaine, 2017) in the 'doc\Related reports (PRMS,MODFLOW,CRT)' subdirectory for documentation on the dynamic parameters, water-use, and lake simulation options.

MODFLOW Files: Up-to-date descriptions of the input requirements for all MODFLOW-2005 and MODFLOW-NWT Packages and Processes are provided in the *Online Guide to MODFLOW-2005* (http://water.usgs.gov/ogw/modflow/MODFLOW-2005-Guide/) and *Online Guide to MODFLOW-NWT* (http://water.usgs.gov/ogw/modflow-nwt/MODFLOW-NWT-Guide/).

DOCUMENTATION AND ADDITIONAL RESOURCES

GSFLOW Online Documentation:
- http://wwwbrr.cr.usgs.gov/projects/SW_MoWS/GSFLOW.html
- http://water.usgs.gov/ogw/gsflow/index.html.

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., http://pubs.usgs.gov/tm/tm6d1/. File **tm6d1_GSFLOW.pdf** in the 'doc' subdirectory of the GSFLOW release)

Additional MODFLOW and PRMS Documentation:
PDFs of the seven reports listed below are provided in the 'doc\Related reports (PRMS,MODFLOW,CRT)' subdirectory of the GSFLOW 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. 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., http://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., http://dx.doi.org/10.3133/tm6B7. File **tm6b7_PRMS-IV.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. 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**.

- 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., http://dx.doi.org/10.3133/tm6D3/. File **tm6d3_Restart.pdf**.

Documentation and additional resources for PRMS and MODFLOW are available at http://wwwbrr.cr.usgs.gov/projects/SW_MoWS/PRMS.html and http://water.usgs.gov/ogw/modflow/, 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.

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.

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.

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.

FUNCTIONALITY, Version 2.0.0

PRMS Modules and Utility Routines (listed in computation order; all are modules, unless noted; <mark>yellow</mark> highlight designates new modules for this version]

basin	Basin Module
climateflow	Climate and Flow Parameters and Variables Input (Utility Routine)
cascade	Cascading-Flow Module
obs	Observed-Data Module
<mark>dynamic_param_read</mark>	Dynamic Parameter Input Module
<mark>water_use_read</mark>	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
<mark>temp_sta</mark>	Station Air-Temperature-Distribution Module
precip_1sta	One-Station Precipitation-Distribution Module
precip_laps	Lapse-Station Precipitation-Distribution 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[1]	Preprocess Spring and Fall Frost Module
transp_tindex	Temperature Index Based Active Transpiration Period Module
intcp	Precipitation-Interception Module
snowcomp	Snow 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[1]	Ground-Water Reservoir Module
subbasin	Subbasin Module
routing[1]	Stream Network Computations Routing (Utility Routine)
strmflow[1]	Streamflow Module
muskingum[1]	Muskingum Streamflow Routing Module
strmflow_in_out[1]	Streamflow routing with inflow equals outflow for each segment
muskingum_lake[1]	Muskingum Streamflow and Lake Routing 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[1]	PRMS Summary Module
basin_sum[1]	Watershed Flow-Summary Module
map_results	Map Based Output Module
write_climate_hru[1]	Generate Climate-by-HRU Files Preprocess Module
convert_params	Generate PRMS-IV or PRMS-V Parameters Preprocess Module

[1]This module is used for PRMS-only simulations.

[2]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.

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. [yellow highlight designates existing MODFLOW packages that were added to GSFLOW for this version]

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[1]	Drain Package
DRT[1]	Drain and Return Flow Package
ETS[1]	Evapotranspiration Segments Package
EVT[1]	Evapotranspiration Package
IBS[1]	Interbed Storage Package

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

[1]This package is used for MODFLOW-only simulations.

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

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_start_time** is not equal to **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.

RELEASE HISTORY

Current Version, 2.0.0 (May 30, 2019)

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.

A. PRMS and GSFLOW Modules and PRMS utilities

This major release adds new functionality for input of dynamic parameters and water use, Muskingum streamflow routing with simulation of lakes, and output of subbasin, stream segment, and basin variables to CSV files. Code related to water use computations was added to `gwflow`, `srunoff_smidx`, `srunoff_carea`, `routing`, and `intcp`. NOTE: PRMS Restart Files generated by previous versions of GSFLOW are not compatible with the current version, thus they must be regenerated as the simulation time period for the antecedent simulation is written into the file and printed when used.

Several PRMS parameters are deprecated and replaced by new parameters that were added to facilitate automated model calibration. 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` 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.

Also, corrected major bugs in the `potet_pm` and `potet_pt` modules and minor bugs in the `soilzone` and `gwflow` modules. See "Update of PRMS PET modules.pdf" file in the 'doc\Related reports (PRMS,MODFLOW,CRT)' 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.

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 1 in the PRMS Control File to minimize warning messages about parameter values falling outside 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 acceptable, **parameter_check_flag** should be set to 0 and **print_debug** to -1 or -2.

INITIAL CONDITIONS FILES
- Initial Condition Files made with previous PRMS versions are not compatible with this version; thus, they must be regenerated. 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 = read all initial value parameters; 1 = do not read 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**). This option 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 error checking in CBH Files that did not work correctly if a simulation start month and year were earlier than the first month and year in the CBH File.

`soilzone`

- Parameters **soil_moist_max** and **soil_rechr_max** 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.
- 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`

- 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`
- Reads and makes available dynamic parameters by HRU from pre-processed files.
- Dynamic parameters include those that describe 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`
- Reads and makes available water-use data (diversions and gains) from pre-processed files.
- Water can be taken 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. 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.

`muskingum_lake`
- Routes water between segments in the system using Muskingum routing and on-channel water body storage and flow routing. Allows for Lakes to be made up of multiple HRUs.

`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 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 ICNVGFLG=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.f90. 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.

PARMETER 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, similar to MODFLOW input 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 1.2.0 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`.

gw_seep_coef

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

humidity_percent

- This new parameter is an alternative to specifying 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, 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.

B. 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.

Unsatuated-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 IPHDY 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

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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.

Previous Versions

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 **mxsziter**, the maximum number of `soilzone` iterations, is retained. It is recommended that the `soilzone` module iterate until MODFLOW converges by setting **mxsziter** 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 **mxsziter** 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 < ABS(1.0E-6) to ABS(EPSILON(0.0)), which is ABS(1.1920929E-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.

A. 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 snowcover 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.

`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 have caused 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.

`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.

`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.

`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

`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.

`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*.
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*

B. 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.

A. 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).

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

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 >= 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. 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: coef_kt = 0.00185*(temp_dif**2) – 0.0433*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 (PRMS, MODFLOW, CRT) 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 (PRMS, MODFLOW, CRT) 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 (PRMS, MODFLOW, CRT) 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 *apk_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 **nhrucell** not equal **ngwcell** and **gvr_hru_id** needed when **nhru** not equal **nhrucell**.

`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 precip < 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 treat them as 0.0.

B. 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*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 TOP-BOT<100*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
        DBDGAMMA     = 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
        DBDGAMMA    = 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
        DBDGAMMA    = 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 proceeded 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 mulitplied 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 proceeded 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 < CELTOP-EXTDP,   ET is zero;
    CELTOP-EXTDP < h < CELTOP-EXTDP+SMOOTHINT,   ET is smoothed; and
    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 proceeded 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.

Previous Versions

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 option 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.

A. 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). 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.

<u>**General Updates and Enhancements**</u>
- <u>Flexible dimension option</u>: 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).

  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) 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; 1means 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 to 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 that 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 SQRT(**coef_lin****2.0+4.0***coef_sq***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 **nhrucell**.

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) <u>**Bug fix**</u>: 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 **nhrucell**.

B. 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.

C. 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 gwfuzfmodule.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_tindex_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 ouput 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.