

GSFLOW Release Notes

Version 2.2.1 – February 24, 2022

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IP-135622

This file describes changes to GSFLOW with each official release. Modules, file names, utility routines, and user input are identified by using `Courier New` font. Input parameters and dimensions are identified by using **bold** font. State and flux variables are identified by using *italic* font. GSFLOW can be used to run PRMS-only and MODFLOW-only simulations (that is, non-integrated simulations) in addition to the integrated GSFLOW mode. This version is based on MODFLOW-NWT version 1.2.0, MODFLOW-2005 version 1.12.0, and PRMS version 5.2.1.

This release (GSFLOW version 2.2.1) adds new functionality for PRMS: a) daily cloud cover time series can be input from a Climate-by-HRU (CBH) file for use in `ccsolrad` module; b) daily snow albedo time series can be input from a Climate-by-HRU (CBH) file for use in `snowcomp` module (specify variable *albedo_day* in the PRMS Data File and parameter **albedo_cbh flag** in the Control File); c) the computation of approximate cloud cover was based on basin variables, it can be optionally computed based on HRU variables, which could be important for large model domains (control parameter **snow_cloudcover_flag**). Also, a few bug fixes were made and a few new parameters and output variables were added. One bug fix affects GSFLOW model results where the model includes swale HRUs. This fix leads to incorrect WB reporting and storage in the gravity reservoir at the intersections of PRMS HRUs and MODFLOW cells. See the RELEASE HISTORY section starting on page 16 that describes changes made for this release as well as previous releases.

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ABSTRACT

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

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

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

GSFLOW operates on a daily time step. The MODFLOW variable-length stress period is retained so that changes in stress or boundary conditions can be specified on any time step. Only the first stress period can be designated as steady for integrated simulations. No computations pertaining to PRMS are executed for an initial steady-state stress period. While PRMS computations always operate on a daily time step, MODFLOW-only simulations support time steps other than daily, and the user can specify the time step length within the MODFLOW

discretization input file. There have been several applications of GSFLOW to real-world systems since the initial release of the software in 2008. Many of these applications are referenced on the USGS GSFLOW webpage (<https://www.usgs.gov/software/coupled-ground-water-and-surface-water-flow-model-gsflow>).

SYSTEM REQUIREMENTS

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

INPUT-FILE INSTRUCTIONS

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

Instructions for preparing 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:

PRMS Files: The file "PRMS_tables_5.2.1.pdf" in the "doc\Related reports" subdirectory that provides updated tables for the PRMS-IV documentation report (Markstrom and others, 2015; <https://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 that are updated in red text indicates new for PRMS-5.2.1; PRMS-5.2.0 are highlighted in red, for PRMS-5.2.0; pink, for PRMS 5.1.0, and green, for PRMS-5.0.0.

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* (<https://water.usgs.gov/ogw/modflow/MODFLOW-2005-Guide/>) and *Online Guide to MODFLOW-NWT* (<https://water.usgs.gov/ogw/modflow-nwt/MODFLOW-NWT-Guide/>). Updated input instructions for the SFR2, UZF1, and AG Package are included in the ‘doc’ subdirectory of the GSFLOW release.

DOCUMENTATION AND ADDITIONAL RESOURCES

GSFLOW Online Documentation:

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

GSFLOW Primary Documentation:

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

Additional MODFLOW and PRMS Documentation:

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

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., <https://pubs.usgs.gov/tm/tm6d2/>. File **tm6d2_CRT.pdf**.

Markstrom, S.L., Regan, R.S., Hay, L.E., Viger, R.J., Webb, R.M.T., Payn, R.A., and LaFontaine, J.H., 2015, PRMS-IV, the precipitation-runoff modeling system, version 4: U.S. Geological Survey Techniques and Methods, book 6, chap. B7, 158 p., <https://dx.doi.org/10.3133/tm6B7>. File <https://pubs.usgs.gov/tm/tm6b7/> **PRMS-IV.pdf**.

Mastin, M.C., 2009, Watershed models for decision support for inflows to Potholes Reservoir, Washington: U.S. Geological Survey Scientific Investigations Report 2009–5081, 54 p., <https://pubs.usgs.gov/sir/2009/5081/pdf/sir20095081.pdf>. File **sir20095081_cfgi**.

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**.

Niswonger, R. G., 2020, An Agricultural Water Use Package for MODFLOW and GSFLOW. Environmental Modelling & Software, 104617. File **AG_Package_EM&S.pdf**.

Regan, R.S., and LaFontaine, J.H., 2017, Documentation of the dynamic parameter, water-use, stream and lake flow routing, and two summary output modules and updates to surface-depression storage simulation and initial conditions specification options with the Precipitation-Runoff Modeling System (PRMS): U.S. Geological Survey Techniques and Methods, book 6, chap. B8, 60 p., <https://doi.org/10.3133/tm6B8>. File **tm6b8_PRMS_enhancements.pdf**.

Regan, R.S., Markstrom, S.L., Hay, L.E., Viger, R.J., Norton, P.A., Driscoll, J.M., LaFontaine, J.H., 2018, Description of the National Hydrologic Model for use with the Precipitation-Runoff Modeling System (PRMS): U.S. Geological Survey Techniques and Methods, book 6, chap B9, 38 p., <https://doi.org/10.3133/tm6B9>. File **tm6b9_nhm_prms.pdf**.

Regan, R.S., Niswonger, R.G., Markstrom, S.L., and Barlow, P.M., 2015, Documentation of a restart option for the U.S. Geological Survey coupled groundwater and surface-water flow (GSFLOW) model: U.S. Geological Survey Techniques and Methods, book 6, chap. D3, 19 p., <https://dx.doi.org/10.3133/tm6D3/>. File **tm6d3_Restart.pdf**.

Sanders, M.J., Markstrom, S.L., Regan, R.S., and Atkinson, R.D., 2017, Documentation of a daily mean stream temperature module—An enhancement to the Precipitation-Runoff Modeling System: U.S. Geological Survey Techniques and Methods, book 6, chap. D4, 18 p., <https://doi.org/10.3133/tm6D4>. File **tm6d4_stream_temp.pdf**.

Van Beusekom, A.E., and Viger, R.J., 2015, A glacier runoff extension to the Precipitation Runoff Modeling System, Journal of Geophysical Research: Earth Science, 21 p.,

<https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2015JF003789>. File glacier_2016_VanBeusekom.

Documentation and additional resources for PRMS and MODFLOW are available at <https://www.usgs.gov/software/precipitation-runoff-modeling-system-prms> and <https://www.usgs.gov/mission-areas/water-resources/science/modflow-and-related-programs>, respectively.

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

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

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

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

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

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

FUNCTIONALITY, Version 2.2.1

PRMS Modules and Utility Routines [listed in computation order; all are modules and written in the FORTRAN programming language, unless noted. Note, additional modules and routines can be easily added that are written in FORTRAN, C, and other languages that can be linked to those languages.

```
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```

prms_constants	Defined Constants (Initialization Utility)
mmf	Data-Structure and Utility Routines (written in the C language)
basin	Basin Module
climateflow	Climate and Flow Parameters and Variables Input (Utility Routine)
cascade	Cascading-Flow Module
obs	Observed-Data Module
dynamic_param_read	Dynamic Parameter Input Module
water_use_read	Water-Use Input Module
prms_time	Time Variable Computation (Utility Routine)
soltab	Potential Solar-Radiation Module
temp_1sta	One-Station Air-Temperature-Distribution Module
temp_laps	Lapse-Station Air-Temperature-Distribution Module
temp_dist2	Inverse-Distance Air-Temperature-Distribution Module
temp_map	Area-Weighted Mapping of Input Temperature Data Module
temp_sta	Station Air-Temperature-Distribution Module
precip_1sta	One-Station Precipitation-Distribution Module
precip_laps	Lapse-Station Precipitation-Distribution Module
precip_map	Area-Weighted Mapping of Input Precipitation Data Module
precip_dist2	Inverse-Distance Precipitation-Distribution Module
xyz_dist	Multiple Linear Regression Precipitation and Temperature-Distribution Module
ide_dist	Inverse Distance and Elevation Precipitation and Temperature-Distribution Module
climate_hru	Pre-computed and Distributed Climate Module
ddsolrad	Degree-Day Solar-Radiation Distribution Module
ccsolrad	Cloud-Cover Solar-Radiation Distribution Module
potet_jh	Jensen-Haise Potential-Evapotranspiration Module
potet_hamon	Hamon Potential-Evapotranspiration Module
potet_pan	Pan-Evaporation Potential-Evapotranspiration Module
potet_hs	Hargreaves and Samani Potential-Evapotranspiration Module
potet_pt	Priestly-Taylor Potential-Evapotranspiration Module

potet_pm	Penman–Monteith Potential-Evapotranspiration Module that uses wind-speed and humidity data specified in CBH Files
potet_pm_sta	Penman–Monteith Potential-Evapotranspiration Module that uses wind-speed and humidity data specified in the PRMS Data File
transp_frost	Frost Based Active Transpiration Period Module
frost_date ¹	Preprocess Spring and Fall Frost Module
transp_tindex	Temperature Index Based Active Transpiration Period Module
intcp	Precipitation-Interception Module
snowcomp	Snow Dynamics Module
glacr_melt	Glacier Dynamics Module
srunoff_smidx	Nonlinear source Area Surface-Runoff and Infiltration Module
srunoff_carea	Linear Source Area Surface-Runoff and Infiltration Module
soilzone	Soil-Zone Module
gwflow 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
muskingum_mann ¹	Muskingum Streamflow Routing using Manning’s N Module
strmflow_in_out ¹	Streamflow routing with inflow equals outflow for each segment
muskingum_lake ¹	Muskingum Streamflow and Lake Routing Module
stream_temp ¹	Stream Network Temperature Module
water_balance	Water Balance Debug (Utility Routine)
nhru_summary	Write User-Selected HRU-based Variables to CSV File Module
nsegment_summary	Write User-Selected Stream Segment Variables to CSV File Module
nsub_summary	Write User-Selected Subbasin Variables and HRU-based Variables Summarized by Subbasins to CSV File Module
basin_summary	Write User-Selected Basin Variables to CSV File Module
prms_summary 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

¹This module is used for PRMS-only simulations.

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

GSFLOW Modules

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

MODFLOW Packages

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

BAS	Basic Package
BCF	Block-Centered Flow Package
UPW	Upstream-Weighting Flow Package
LPF	Layer-Property Flow Package
HUF	Hydrogeologic-Unit Flow Package
HFB	Horizontal Flow Barrier Package
DRN 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
AG	Agriculture Package
GAG	Gage Package
MNW1	Version 1 of the Multi-Node Well Package
MNW2	Version 2 of the Multi-Node Well Package

SWI 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)

¹This package is used for MODFLOW-only simulations.

FREQUENTLY ASKED QUESTIONS:

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

The restart option for GSFLOW (Regan and others, 2015) provided a capability to start a model for a time that follows the beginning of the stress period data defined in MODFLOW input packages. Non-restart simulations also can have a starting time that is later than the first stress period defined in MODFLOW. Thus, a GSFLOW simulation could start at a time that is after the first stress period defined in MODFLOW. This condition requires the user to define the Control parameters `modflow_time_zero` and `start_time` that are the date (year, month, day) that defines the time of the first stress period in MODFLOW and time the simulation starts, respectively. Having a `modflow_time_zero` that is different than `start_time` impacts the meaning of several MODFLOW variables that are used for referencing time in a simulation and for output control. These variables include the stress period (KPER), time step (KSTP), total time (TOTIM), and stress period time (PERTIM). Definitions are provided here for clarification on these variables for simulations when `modflow_time_zero` is not equal to `start_time`. The values of KPER and KSTP have implications throughout MODFLOW packages, for example, the OBS Packages reference the time for observation values using KPER and KSTP. Special consideration of KPER and KSTP should be given when using values for `modflow_time_zero` that are not the same as `start_time`.

KPER Global stress period number, where stress period 1 begins at `modflow_time_zero` and increments consecutively to the end of the simulation.

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

TOTIM Global model time, where TOTIM is zero at **modflow_time_zero** and increments consecutively to the end of the simulation.

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

CONTROLLING SCREEN OUTPUT

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

FLEXIBLE DIMENSIONS FOR PRMS PARAMETERS

There are several ways to specify parameters. Traditionally, a single value is specified per line. However, multiple values can be specified per line if fewer than 12,000 characters are specified and there are no trailing blanks. This might be useful to specify a parameter as a grid of values, similar to MODFLOW input as columns by rows with the upper left value specified for column 1 row 1 and the bottom right value specified for last column and last row.

Previously, parameters had only one option for the number of values (dimension(s)) specified in the Parameter File. Now, most parameters can be specified using the maximum dimension(s) or using compatible dimensions up to a maximum number of values based on the specified dimension(s). This parameter specification capability is referred to as the flexible dimension option. Options for specifying a parameter with a maximum dimension of **nhru,nmonths** are using a single dimension: **one**, **nmonths**, **nsub**, or **nhru**, or double dimensions: **nsub,nmonths**, and **nhru,nmonths**. The dimension options for a parameter with a maximum dimension of **nhru** are **one**, **nsub**, and **nhru**. The dimension options for a parameter with a maximum dimension of **nssr** are **one**, **nsub**, and **nssr**. The dimension options for a parameter with a maximum dimension of **ngw** are **one**, **nsub**, and **ngw**. PRMS will read the dimension, number of values, and values from the Parameter File. If the parameter is not specified at the maximum dimension, the parameter values will be automatically expanded to the maximum dimension by the code. Thus, the user has several options to specify the number of parameter values based

on the spatial and temporal variability, available data, or for some other purpose. Additionally, the number of lines in Parameter Files can be significantly reduced by specifying a single (dimension **one**) or **nsub** values for parameters that have a constant value for all HRUs or subbasins.

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

Note, that using different number of values may change results when dimensions are specified greater than the original dimension(s) of older models while allowing for increased ability to calibrate spatially and temporally. Maximum parameter dimensions are identified in updated tables 1-1 and 1-3 that are found in the file 'PRMS_tables_5.2.1.pdf'.

PRMS INITIAL CONDITIONS FILES

The PRMS Initial Conditions File is read whenever control parameter **init_vars_from_file** is specified > 0. Various initial states can be updated for a restart simulation using initial value parameters as specified in the PRMS Parameter File depending on the value of **init_vars_from_file** (0 = do not read Initial Conditions File and use all initial value parameters as read from PRMS Parameter File; 1 = read all initial value parameters; 2 = read **dprst_frac_init**, **snowpack_init**, **segment_flow_init**, **elevlake_init**, **gwstor_init**, (**soil_rechr_init**, **soil_moist_init**, **ssstor_init** for **model_mode** = PRMS or GSFLOW) or (**soil_rechr_init_frac**, **soil_moist_init_frac**, **ssstor_init_frac** for **model_mode** = PRMS5 or GSFLOW5), and **stream_tave_init**; 3 = read **snowpack_init**; 4 = read **elevlake_init**; 5 = read (**soil_rechr_init_frac**, **soil_moist_init_frac**, **ssstor_init_frac** for **model_mode** = PRMS5 or GSFLOW5); 6 = read **gwstor_init**; 7 = read **dprst_frac_init**; 8 = read **stream_tave_init**). Options 2 and 3 could be used, for example, to update the snowpack in a restart simulation by specifying values for **snowpack_init** to reflect an observed or model snow water equivalent data set. Option 8 could be used, for example, to update the stream temperature in each segment in a restart simulation by specifying values for **stream_tave_init** to reflect an observed or model stream temperature data set.

Options that cannot change for a restart simulation include: a) surface depression storage simulation option; b) cascading flow simulation option; c) dimensions **nhru**, **nssr**, **ngw**, **nsegment**, **nhrucell**, **nlake**; d) the model mode (GSFLOW, PRMS-only, or MODFLOW-only); and e) use of modules **temp_1sta**, **temp_laps**, **temp_dist2**, **potet_pan**, **transp_tindex**.

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

MODEL MODES

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

`GSFLOW5`, `PRMS5`, `gsflow5` – This mode uses the parameters **tmax_allrain_offset**, **soil_rechr_max_frac**, **soil_rechr_init_frac**, **soil_moist_init_frac**, **ssstor_init_frac**, **sro_to_dprst_perv**, and **dprst_frac**

`PRMS`, `prms`, `PRMS4`, `prms4`, or `DAILY` – This mode uses the parameters **tmax_allrain**, **soil_rechr_max**, **soil_rechr_init**, **soil_moist_init**, **ssstor_init**, **sro_to_dprst**, and **dprst_area**.

`CONVERT` – This mode computes and produces the file `PRMS_5.params` that contains parameters **tmax_allrain_offset**, **soil_rechr_max_frac**, **soil_rechr_init_frac**, **soil_moist_init_frac**, **ssstor_init_frac**, **sro_to_dprst_perv**, and **dprst_frac** used in a `PRMS5` simulation on the basis of an existing Parameter File used with a `PRMS4` simulation. The deprecated `PRMS4` parameters can be removed from the existing Parameter File.

`CONVERT4` – This mode computes and produces the file `PRMS_4.params` that contains parameters **tmax_allrain**, **soil_rechr_max**, **soil_rechr_init**, **soil_moist_init**, **ssstor_init**, **sro_to_dprst**, and **dprst_area** used in a `PRMS4` simulation on the basis of an existing Parameter File used with a `PRMS5` simulation. The `PRMS5` parameters can be removed from the existing Parameter File.

`FROST` – This mode computes and writes the file `frost_date.param` of frost parameters (**spring_frost** and **fall_frost**) using the **frost_date** module that can be used by the **transp_frost** module in subsequent simulations. Simulation includes reading input (Data File, CBH File(s), Dynamic Parameter File(s), and Water-Use File(s)) and computing temperature and precipitation processes. All other processes are not computed.

`WRITE_CLIMATE` – This mode computes and writes Climate-by-HRU (CBH) File(s) for all climate processes that have the module parameters **precip_module**, **temp_module**, **et_module**, **swrad_module**, and/or **transp_module** specified as **climate_hru**. The filenames for CBH Files are specified by the control parameter; these are: **precip_day** (**precip_module**); **tmax_day** and **tmin_day** (**temp_module**); **potet_day** (**et_module**); **swrad_day** (**swrad_module**); and **transp_day** (**transp_module**). The generated CBH

File(s) can be used by the **climate_hru** module in subsequent simulations. The simulation reads input files (Data File, CBH File(s), Dynamic Parameter File(s), and/or Water-Use File(s)) and computes temperature, precipitation, solar radiation, transpiration, and potential evapotranspiration processes, and writes requested CBH files. All other processes are not computed.

CLIMATE – This mode computes climate processes only. The simulation reads input files (Data File, CBH File(s), Dynamic Parameter File(s), and/or Water-Use File(s)) and computes temperature and precipitation. All other processes are not computed.

POTET – This mode computes processes through potential evapotranspiration. The simulation reads input files (Data File, CBH File(s), Dynamic Parameter File(s), and/or Water-Use File(s)) and computes temperature, precipitation, solar radiation, transpiration, and potential evapotranspiration processes. All other processes are not computed.

TRANSPIRE – This mode computes processes through transpiration (active growing season). The simulation will only read input files (Data File, CBH File(s), Dynamic Parameter File(s), and Water-Use File(s)) and compute temperature, precipitation, solar radiation, and transpiration. All other processes are not computed.

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

RELEASE HISTORY

Version 2.2.1 (February 24, 2022)

This version of GSFLOW is based on MODFLOW-NWT version 1.2, MODFLOW-2005 version 1.12.0, and PRMS version 5.2.1. 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.

PRMS Modules

Version dates of modules were updated.

GSFLOW

The variable *hru_storage* computes PRMS storage for GSFLOW mode that does not include groundwater storage

Binary CBH Files are opened as FORM=UNFORMATTED and ACCESS=STREAM for both Windows and Linux executables. Previously Windows was opened with FORM=BINARY.

BUG FIXES

soilzone

- There was incorrect water balance reporting and storage in the gravity reservoir at the intersections of PRMS HRUs and MODFLOW cells for GSFLOW model results for models that include swale HRUs that had water content greater than the value of **sat_threshold**. This was due to the actual evapotranspiration was not subtracted from the gravity reservoir storage. The overall simulation solution is not affected, but the reporting in the water-budget file is incorrect for storage in the gravity reservoir, ET from the capillary reservoir and from swale HRUs. This fix affects GSFLOW mode simulations and not PRMS-only or MODFLOW-only simulations.

precip_dist2

- Parameter **max_psta** was declared as a real instead of integer. This did not affect computations.

temp_dist2

- Parameter **max_tsta** was declared as a real instead of integer. This did not affect computations.

intcp

- *gain_inches* is now set to the unit water depth in the canopy instead of based on how the water is applied. *gain_inches_hru* is the unit water depth over the HRU.
- *basin_changeover* was dimensioned incorrectly by **nhru** instead of **one**.

cascade

- **gw_up_id** was set to a single value of **hru_up_id** instead of all values parameter **hru_segment** was used to define cascading flow (control parameter **cascade_flag** specified = 2).

`intcp, srunoff_smidx, srunoff_carea, and water_balance`

- The *use_sroff_transfer* flag was used to determine if *net_apply* from `intcp` was set to 1 when the canopy application is read from `water_use_read`, which was set whenever `water_use_read` is active. However, the *use_intcp_transfer* flag is set to 1 only when canopy irrigation is active. This latter flag is now used so that the code is slightly more efficient.

`potet_pm, potet_pt, and climate_hru`

- **humidity_cbh_flag** (flag to specify to read a CBH file with humidity values) and **humidity_day** (filename of the humidity CBH file) control parameters were ignored.

`potet_pm` and `climate_hru`

- **windspeed_cbh_flag** (flag to specify to read a CBH file with windspeed values) and **windspeed_day** (filename of the windspeed CBH file) control parameters were ignored.

`stream_temp`

- Computation of *seg_tave_lat* moved before calculation of the water temperature at the beginning of the time step.

NEW FUNCTIONALITY

`snowcomp`

- The computation of approximate cloud cover as the ratio of measured radiation to potential radiation was based on basin variables, it can be optionally computed based on HRU variables, which could be important for large model domains, when control parameter **snow_cloudcover_flag** is specified equal to 1. The HRU equation is:

$$\text{orad} = \text{Swrad}(\text{ihru}) * \text{Hru_cossl}(\text{ihru}) * \text{Soltab_horad_potsw}(\text{Jday}, \text{ihru}) / \text{Soltab_potsw}(\text{Jday}, \text{ihru})$$

$$\text{cloud cover} = \text{orad} / \text{Soltab_horad_potsw}(\text{Jday}, \text{ihru})$$

- A daily snow albedo time series can be input from a Climate-by-HRU (CBH) file, the CBH filename is specified by control parameter **albedo_day** and is read when control parameter **albedo_cbh_flag** is specified equal to 1.

`climate_hru`

- Added reading of albedo and cloud cover CBH Files.

PARAMETER CHANGES

New Parameters read from the Control File:

albedo_cbh_flag

- Flag to indicate if snowpack albedo is read from a CBH File (0=no; 1=yes)

albedo_day

- Filename of snowpack albedo CBH File

snow_cloudcover_flag

- Flag to indicate if approximation of cloud cover for snowpack computations is computed using HRU dimensioned variables (0=no; 1=yes)

cloud_cover_cbh_flag

- Flag to indicate if cloud cover for use in `ccsolrad` is read from a CBH File (0=no; 1=yes)

cloud_cover_day

- Filename of cloud cover CBH File

NEW VARIABLES

`intcp`

- *gain_inches* and *gain_inches_hru* – application water to the canopy as a) depth in canopy and b) depth over the HRU, respectively. Both have units of inches.

`climate_hru`

- *albedo_hru* – Snowpack albedo of each HRU read from CBH File, units of decimal fraction.
- *cloud_cover_cbh* – Cloud cover of each HRU read from CBH File, units of decimal fraction.

`water_use_read`

- *soilzone_gain_hru* – Irrigation added to soilzone as depth over each HRU in units of inches.

MODFLOW Packages

GSFLOW version 2.2.1 is based on MODFLOW-NWT version 1.2 and some additional changes made since this last release. MODFLOW-2005 source files used in MODFLOW-NWT were updated to reflect changes made for MODFLOW-2005 version 1.12.0. Since the last GSFLOW release (version 1.2.2), there has been one MODFLOW-NWT releases (version 1.2). Changes made to MODFLOW-NWT and MODFLOW-2005 also are described in the release notes for those codes; users are encouraged to review those release notes in addition to the notes provided below.

Changed files: `gwf2sfr7_NWT.f`, `gwfsfrmodule_NWT.f`, `gwf2uzf1_NWT.f`, `gwf2lak7_NWT.f`, `lrestart.f`, `NWT1_solver.f`, `NWT1_xmdlib.f`, `gwf2mnw27_NWT.f`, `gwf2upw1.f`

Lake (LAK) Package

- A check was added to initialize state variables for transient simulations that are not using restart data for initial conditions. Previously, lake stage was not getting set to the value specified in the LAK input file if the model was starting after `modflow_time_zero`.
- A bug was fixed that would incorrectly use the dynamic lake area for calculating precipitation and ET on lakes in GSFLOW mode. ET and precipitation on lakes in GSFLOW mode is calculated using a fixed area as defined by the number of lake type HRUs.

- Previously, a derivative value of zero was checked to determine if the Newton method should be used to calculate lake stage, this small non-zero value is now used instead of zero to avoid machine precision affecting the check for near linearity.

Unsaturated-Zone Flow (UZF) Package

- The option to use the input variable SURFK to calculate surface leakage was not set for GSFLOW simulations. GSFLOW simulations can use SURFK to calculate surface leakage if SPECIFYSURFK and SEEPSURFK are specified.

Streamflow Routing (SFR) Package

- The variable NUMTAB was changed to NUMTAB_SFR to avoid confusion with other packages that use this variable name.

Newton Solver (NWT) Package

- Previously the Newton Solver set groundwater cells surrounded by inactive cells to inactive. These cells also were mistakenly set equal to HDRY. This mistake was corrected by setting cells made inactive to HNOFLO.
- The source file NWT1_xmdlib.f was modified to replace a condensed (implicit) loop to an expanded do loop to avoid inconsistent memory access errors.

Restart Option

- MODFLOW restart data previously was saved to files using the “BINARY” format option. The format for MODFLOW restart data was changed to “UNFORMATTED.” Additionally, the variable BUFF that is used to store restart data for output was set equal to groundwater head (HNEW) without explicit element references. This was changed to set these variables using explicit array elements and Fortran “DO” statements.

Multi-Node Well (MNW2) Package

- A variable was initialized that was not previously.

Upstream Weighting (UPW) Package

- Unused variables were removed.

Previous Versions

Version 2.2.0 (January 20, 2021)

This version of GSFLOW (2.2.0) is based on MODFLOW-NWT version 1.2, MODFLOW-2005 version 1.12.0, and PRMS version 5.2.0. 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. Changes not listed below:

- Initial Condition Files (i.e., Restart Files or antecedent conditions files) generated by previous versions of GSFLOW are not compatible with this version, thus they must be regenerated. Previous versions are not compatible because many basin area-weighted variables from prior versions of Restart Files are not needed to restart a simulation and are no included in the Initial Conditions Files.
- New files are: `prms_constants.f90` (contains constant values that are used by many modules that are used to improve code readability and consistency of numerical constants; some constants are new and others moved from `call_modules.f90` and `basin.f90`); `glacr_melt.f90` (glacier dynamics module); `precip_temp_map.f90` (precipitation and temperature distribution modules on the basis of mapping from input file to HRUs).
- Changed how module version dates and descriptions are printed to screen and increased consistency in module declarations.
- Water use information applied in associated PRMS process modules instead of in module `water_use_read`. For example, transfers to/from PRMS lakes are applied in `muskingum_lake` and transfers to/from surface depression storage are applied in `srunoff_smidx` and `srunoff_carea`. The transfers were already applied in `soilzone`, `intcp`, and `gwflow`.
- There have been numerous changes to the `stream_temp` module since the previous release to address bugs. This version of the module will give significantly different simulation results than previous versions. Any modeling work done with previous versions of this module should be redone with this (or subsequent) releases.
- The `gsflow.log` file is no longer written.

PRMS and GSFLOW Modules and PRMS utilities

BUG FIXES – by module:

`dynamic_parameter_read`

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

`muskingum` and `muskingum_mann`

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

snowcomp

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

stream_temp

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

mmf.c

- Removed an extra argument to three usages of routine `fprintf` that were used to issue warning messages.

NEW FUNCTIONALITY

prms_constants.f90

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

precip_map

- This module distributes precipitation to each HRU using precipitation data specified in a Map File as a time series of gridded or other spatial units using an area-weighted method and a correction factor to account for differences in altitude, spatial variation, topography, and data accuracy between the spatial scale of the values specified in the Map File and HRUs. The module requires daily input, thus, any

temporal discrepancies (i.e., the values in the Map File are valid for noon one day to noon of the second day are not considered. Values are assumed to be valid for each full day. The Map File is a text file with each day specified by a date and time (year, month, day, hour, minute, second) followed by **nhru** values in order of HRU 1 through **nhru**. Each value can be separated by a space and/or comma. The values for hour, minute and second are specified as 0. For example, the date and time of 2021/1/20 12:15:00:00 can be specified as: 2021 1 20 12 15 0 0 0. Any number of lines can be used to specify each day. For example, if the HRUs are a grid, one way to specify a day is the date on one line followed by values in a gridded format with the number of lines equal to the number of rows in the grid and the number of values on a line equal to the number of columns in the grid. Each HRU is associated with one or more values in the Map File as a fraction based on an intersection of the HRU map and gridded or other map. Use of this option can increase execution speed by reducing the volume of input read during a simulation for models that would require very large climate-by-HRU (CBH) Files that are typically pre-processed distributions of gridded data. Typically, the source gridded data file is much smaller than a CBH File. Additionally, the module allows for calibration adjustments using parameters. See below and/or in the file “PRMS_tables_5.2.docx” for a description of the required dimensions and parameters, each are labeled with `precip_map` (dimensions **nmap** and **nmap2hru**, parameters **hru2map_id**, **hru2map_pct**, **map2hru_id**, and **precip_map_adj**)

temp_map

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

typically pre-processed distributions of gridded data. Typically, the source gridded data file is much smaller than a CBH File. See below and/or in the file “PRMS_tables_5.2.docx” for a description of the required dimensions and parameters, each are labeled with `precip_map` (dimensions `nmap` and `nmap2hru`, parameters `hru2map_id`, `hru2map_pct`, `map2hru_id`, and `temp_map_adj`)

- Additionally, the module allows for calibration adjustments using parameters.

`glacr_melt`

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

Frozen ground dynamics

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

Stop conditions

- ERROR messages issued by modules have been reworded to be more consistent in format. Additionally, in ERROR messages and at the termination of a simulation a value is output. A non-zero value indicates an ERROR was detected in the simulation. The values are output according to the following list:

-4 = read input error
-3 = open output file error
-2 = open input file error
-1 = write output error
0 = no error
1 = control parameter error
2 = variable range error
3 = dimension range error
4 = parameter range error
5 = data file input error
6 = timestep error

- 7 = air temperature range error
- 8 = streamflow range error
- 9 = basin module error
- 10 = Climate-by-HRU (CBH) input error
- 11 = Cascade input error
- 12 = Restart file error
- 13 = Dynamic parameter error
- 14 = Water-use error
- 15 = get of parameter or variable error
- 16 = module error
- 17 = lake error
- 18 = soilzone error

NEW DIMENSIONS

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

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

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

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

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

PARAMETER CHANGES

New Parameters read from the Control File:

frozen_flag

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

glacier_flag

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

mblnit_flag

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

stream_temp_shade_flag

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

PRMS_iteration_flag

- Flag to indicate if interception, snow dynamics, surface runoff, and depression storage computations, in addition to soilzone processes, in the MODFLOW iteration loop (0=no, only soilzone computations in the MODFLOW iteration loop)

outputSelectDatesON_OFF

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

selectDatesFileName

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

New Parameters: read from Parameter Files

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

hru2map_id – used in modules `temp_map` and `precip_map`

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

hru2map_pct – used in modules `temp_map` and `precip_map`

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

map2hru_id – used in modules `temp_map` and `precip_map`

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

precip_map_adj – used in module `precip_map`

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

tmax_map_adj – used in module `temp_map`

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

tmin_map_adj – used in module `temp_map`

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

cfgi_decay – used in frozen ground simulation option

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

cfgi_thrshld – used in frozen ground simulation option

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

Updated Parameters read from a Parameter File:

hru_type

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

adjust_rain and **adjust_snow**

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

rain_adj

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

ssr2gw_rate

- The units were corrected to be inches/day and the maximum suggested value increased to 999.0. It is used in the `soilzone` module.

width_alpha

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

NEW VARIABLES

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

gwflow

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

basin

- **hru_elev_ts** – HRU elevation for timestep, which can change for glaciers.

MODFLOW Packages

GSFLOW version 2.2.0 is based on MODFLOW-NWT version 1.2 and some additional changes made since this last release. MODFLOW-2005 source files used in MODFLOW-NWT were updated to reflect changes made for MODFLOW-2005 version 1.12.0. Since the last GSFLOW release (version 1.2.2), there has been one MODFLOW-NWT releases (version 1.2). Changes

made to MODFLOW-NWT and MODFLOW-2005 also are described in the release notes for those codes; users are encouraged to review those release notes in addition to the notes provided below.

Changed files: gwf2sfr7_NWT.f, gwf2uzf1_NWT.f, gwf2lak7_NWT.f, gwf2ag1_NWT.f, lrestart.f

Lake (LAK) Package

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

Restart utility for MODFLOW

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

Streamflow Routing (SFR2) Package

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

Agriculture (AG) Package

- Two bugs were fixed in this package. The first bug resulted in an error in how the supplemental pumping was calculated for models that conjunctively use surface water and groundwater. The second bug fixes how results were output to the timeseries output files for diversions and supplemental pumping. Finally, for integrated GSFLOW simulations actual ET included only ET in the PRMS soilzone. Actual ET calculated in the unsaturated and saturated zones beneath the soil zone are included in the calculation of actual ET for the crop.

Unsaturated-Zone Flow (UZF1) Package

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

Version 2.2.0 (March 04, 2020)

This version of GSFLOW (2.2.0) is based on MODFLOW-NWT version 1.2, MODFLOW-2005 version 1.12.0, and PRMS version 5.2.0. 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. Changes not listed below:

- Initial Condition Files (i.e., Restart Files or antecedent conditions files) generated by previous versions of GSFLOW are not compatible with this version, thus they must be regenerated. Previous versions are not compatible because many basin area-weighted variables from prior versions of Restart Files are not needed to restart a simulation and are no included in the Initial Conditions Files.
- New files are: `prms_constants.f90` (contains constant values that are used by many modules that are used to improve code readability and consistency of numerical constants; some constants are new and others moved from `call_modules.f90` and `basin.f90`); `glacr_melt.f90` (glacier dynamics module); `precip_temp_map.f90` (precipitation and temperature distribution modules on the basis of mapping from input file to HRUs).
- Changed how module version dates and descriptions are printed to screen and increased consistency in module declarations.
- Water use information applied in associated PRMS process modules instead of in module `water_use_read`. For example, transfers to/from PRMS lakes are applied in `muskingum_lake` and transfers to/from surface depression storage are applied in `srunoff_smidx` and `srunoff_carea`. The transfers were already applied in `soilzone`, `intcp`, and `gwflow`.
- There have been numerous changes to the `stream_temp` module since the previous release to address bugs. This version of the module will give significantly different simulation results than previous versions. Any modeling work done with previous versions of this module should be redone with this (or subsequent) releases.
- The `gsflow.log` file is no longer written.

PRMS and GSFLOW Modules and PRMS utilities

BUG FIXES – by module:

`dynamic_parameter_read`

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

`muskingum` and `muskingum_mann`

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

`snowcomp`

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

`stream_temp`

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

`mmf.c`

- Removed an extra argument to three usages of routine `fprintf` that were used to issue warning messages.

NEW FUNCTIONALITY

`prms_constants.f90`

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

`precip_map`

- This module distributes precipitation to each HRU using precipitation data specified in a Map File as a time series of gridded or other spatial units using an area-weighted method and a correction factor to account for differences in altitude, spatial variation, topography, and data accuracy between the spatial scale of the values specified in the Map File and HRUs. The module requires daily input, thus, any temporal discrepancies (i.e., the values in the Map File are valid for noon one day to noon of the second day) are not considered. Values are assumed to be valid for each

full day. The Map File is a text file with each day specified by a date and time (year, month, day, hour, minute, second) followed by **nhru** values in order of HRU 1 through **nhru**. Each value can be separated by a space and/or comma. The values for hour, minute and second are specified as 0. For example, the date and time of 2021/1/20 12:15:00:00 can be specified as: 2021 1 20 12 15 0 0 0. Any number of lines can be used to specify each day. For example, if the HRUs are a grid, one way to specify a day is the date on one line followed by values in a gridded format with the number of lines equal to the number of rows in the grid and the number of values on a line equal to the number of columns in the grid. Each HRU is associated with one or more values in the Map File as a fraction based on an intersection of the HRU map and gridded or other map. Use of this option can increase execution speed by reducing the volume of input read during a simulation for models that would require very large climate-by-HRU (CBH) Files that are typically pre-processed distributions of gridded data. Typically, the source gridded data file is much smaller than a CBH File. Additionally, the module allows for calibration adjustments using parameters. See below and/or in the file “PRMS_tables_5.2.docx” for a description of the required dimensions and parameters, each are labeled with `precip_map` (dimensions **nmap** and **nmap2hru**, parameters **hru2map_id**, **hru2map_pct**, **map2hru_id**, and **precip_map_adj**)

`temp_map`

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

parameters, each are labeled with `precip_map` (dimensions `nmap` and `nmap2hru`, parameters `hru2map_id`, `hru2map_pct`, `map2hru_id`, and `temp_map_adj`)

- Additionally, the module allows for calibration adjustments using parameters.

`glacr_melt`

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

Frozen ground dynamics

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

Stop conditions

- ERROR messages issued by modules have been reworded to be more consistent in format. Additionally, in ERROR messages and at the termination of a simulation a value is output. A non-zero value indicates an ERROR was detected in the simulation. The values are output according to the following list:

-4 = read input error

-3 = open output file error

-2 = open input file error

-1 = write output error

0 = no error

1 = control parameter error

2 = variable range error

3 = dimension range error

4 = parameter range error

5 = data file input error

6 = timestep error

7 = air temperature range error

- 8 = streamflow range error
- 9 = basin module error
- 10 = Climate-by-HRU (CBH) input error
- 11 = Cascade input error
- 12 = Restart file error
- 13 = Dynamic parameter error
- 14 = Water-use error
- 15 = get of parameter or variable error
- 16 = module error
- 17 = lake error
- 18 = soilzone error

NEW DIMENSIONS

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

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

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

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

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

PARAMETER CHANGES

New Parameters read from the Control File:

frozen_flag

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

glacier_flag

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

mbInnit_flag

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

stream_temp_shade_flag

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

PRMS_iteration_flag

- Flag to indicate if interception, snow dynamics, surface runoff, and depression storage computations, in addition to soilzone processes, in the MODFLOW iteration loop (0=no, only soilzone computations in the MODFLOW iteration loop)

outputSelectDatesON_OFF

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

selectDatesFileName

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

New Parameters: read from Parameter Files

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

hru2map_id – used in modules `temp_map` and `precip_map`

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

hru2map_pct – used in modules `temp_map` and `precip_map`

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

map2hru_id – used in modules `temp_map` and `precip_map`

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

precip_map_adj – used in module `precip_map`

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

tmax_map_adj – used in module `temp_map`

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

tmin_map_adj – used in module `temp_map`

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

cfgi_decay – used in frozen ground simulation option

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

cfgi_thrshld – used in frozen ground simulation option

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

Updated Parameters read from a Parameter File:

hru_type

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

adjust_rain and **adjust_snow**

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

rain_adj

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

ssr2gw_rate

- The units were corrected to be inches/day and the maximum suggested value increased to 999.0. It is used in the `soilzone` module.

width_alpha

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

NEW VARIABLES

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

gwflow

- `lakein_gwflow` – Groundwater flow received from cascading upslope GWRs for each Lake GWR in units of acre-inches.

basin

- `hru_elev_ts` – HRU elevation for timestep, which can change for glaciers.

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Restart utility for MODFLOW

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