Version 2.3.0 of 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)
March 17, 2023

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 1.3.0, MODFLOW-2005 version 1.12.0, and PRMS version 5.3.0.

This release (GSFLOW version 2.3.0) includes refactoring the PRMS data structure, utility routines, reading of input files, and simulation framework previously coded in the C programming language to the FORTRAN programming language. Functionality not refactored and not included in this release are:

a) output of PRMS Animation Files;
b) DOCUMENTATION model mode to produce files of all possible input parameters and output variables;
c) -print command line option to produce files of required parameters and output variables for model configuration;
d) -rtg command line option to produce output used with the PRMS GUI for runtime graphics;

New functionality for PRMS:

a) addition of new soilzone module (`soilzone_ag`) that includes agricultural fraction (parameter **ag_frac**) where soil computations using identical methods as for the pervious capillary water-holding reservoir;
b) restart files can optionally be saved as a text file (control parameter **text_restart_flag**);
c) agricultural fraction can be specified as a time series (control parameter **dyn_ag_frac_flag**) as well as **ag_soil_moist_max** and **ag_soil_rechr_max_frac** (control parameter **dyn_ag_soil_flag**);
d) computation of irrigation water required to meet agricultural demand as based on specified actual and potential evaporation and antecedent soil-water content using an iterative method (control parameter **iter_aet_flag**) included in `soilzone_ag`;
e) computations segment width, depth, area, and velocity based on segment outflow computed by other modules when stream temperature module is active (control parameter **stream_temp_flag**);

f) segment stream temperature values can be specified;

g) streamflow from selected segments can be applied to the capillary reservoir (*soil_moist*) when `soilzone_module` is specified as `soilzone` or capillary reservoir of the agricultural fraction (*ag_soil_moist*) when `soilzone_module` is specified as `soilzone_ag` of selected HRUs (**segment_outflow_id**).

New functionality for GSFLOW:

a) additional PRMS process modules can be included in the MODFLOW iteration loop; three options as specified by **PRMS_land_iteration_flag** (0=soilzone; 1=surface runoff and soilzone; and 3=interception, snow, glacier, surface runoff, and soilzone;

b) water transfers from and to surface-depression storage in GSFLOW simulation mode.

These changes, bug fixes and minor code changes are described in the RELEASE HISTORY section starting on page 17 as well as changes made for 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.2.3.0.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_updated_tables.pdf" in the "doc" 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. Purple text indicates changes for GSFLOW-2.3.0 since PRMS-5.3.0. Blue text indicates changes for PRMS-5.3,0, red text indicates changes for PRMS-5.2.1 from PRMS-5.2.0, while green text indicates deprecated parameters that are retained for downward compatibility with PRMS version 4.

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 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 2.3.0

PRMS Modules and Utility Routines [listed in computation order; all are modules and written in the FORTRAN programming language. Note, additional modules and routines can be easily added that are written in FORTRAN, C, and other languages that can be linked to FORTRAN. Changes for versions 2.3.0 are highlighted in yellow.

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prms_constants	Defined Constants (Initialization Utility)
mmf_utils	Data-Structure, Utility Routines and Data File, Parameter File, and Control File readers, files: c_mmf_utils.f90, c_read_control_file.f90, c_read_data_file.f90, c_read_parameter_file.f90, sm_mmf_utils.f90, sm_read_control_file.f90, sm_read_data_file.f90, sm_read_parameter_file.f90, statvar_out.f90
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

`dynamic_soil_param_read`	Dynamic Parameter Input Module for surface runoff, surface-depression storage, and impervious, pervious, and agriculture fractions; code came from `dynamic_parameter_read`
`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
`cloud_cover`	Cloud-Cover 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
soilzone_ag	Soil-Zone Module used when agricultural fraction within HRUs is specified
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
segment_to_hru[1]	Streamflow Routing Module that allows segment outflow computed by other modules to flow to pervious area of associated HRUs
muskingum_lake[1]	Muskingum Streamflow and Lake Routing Module
strmflow_character[1]	Stream Characteristics Module that computes segment width, depth, area, and velocity based on segment outflow computed by other modules
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

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[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.

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
`gsflow_fortran`	Main program that controls timestep loop
`modsim_diversion_read`	Interface to read MODSIM diversion flows to HRUs
`gsflow_modsim2prms`	Interface to transfer MODSIM diversion flows to HRUs
`gsflow_prms2modsim`	Interface for PRMS flows to MODSIM lakes and segments

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.

AG	Agriculture Package
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])

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

FREQUENTLY ASKED QUESTIONS:

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

The restart option for GSFLOW (Regan and others, 2015) provided a capability to start a model for a time that follows the beginning of the stress period data defined in MODFLOW input packages. Non-restart simulations also can have a starting time that is later than the first stress period defined in MODFLOW. Thus, a GSFLOW simulation could start at a time that is after the first stress period defined in MODFLOW. This condition requires the user to define the Control parameters **modflow_time_zero** and **start_time** that are the date (year, month, day) that defines the time of the first stress period in MODFLOW and time the simulation starts, respectively. Having a **modflow_time_zero** that is different than **start_time** impacts the meaning of several MODFLOW variables that are used for referencing time in a simulation and

for output control. These variables include the stress period (KPER), time step (KSTP), total time (TOTIM), and stress period time (PERTIM). Definitions are provided here for clarification on these variables for simulations when **modflow_time_zero** is not equal to **start_time**. The values of KPER and KSTP have implications throughout MODFLOW packages, for example, the OBS Packages reference the time for observation values using KPER and KSTP. Special consideration of KPER and KSTP should be given when using values for **modflow_time_zero** that are not the same as **start_time.**

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

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

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

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

CONTROLLING SCREEN OUTPUT

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

FLEXIBLE DIMENSIONS FOR PRMS PARAMETERS

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

Previously, parameters had only one option for the number of values (dimension(s)) specified in the Parameter File. Now, most parameters can be specified using the maximum dimension(s) or using compatible dimensions 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 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 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
        Parameter File;
1 = read all initial value parameters;

2 = read **dprst_frac_init**, **snowpack_init**, **segment_flow_init**, **elevlake_init**, **gwstor_init**,
      (**soil_rechr_init**, **soil_moist_init**, **ssstor_init** for **model_mode** = PRMS or GSFLOW) or
      (**soil_rechr_init_frac**, **soil_moist_init_frac**, **ssstor_init_frac** for **model_mode** = PRMS5
      or GSFLOW5), and **stream_tave_init**;

3 = read **snowpack_init**;

4 = read **elevlake_init**;

5 = read (**soil_rechr_init_frac**, **soil_moist_init_frac**, **ssstor_init_frac** for **model_mode** = PRMS5
      or GSFLOW5);

6 = read **gwstor_init**;

7 = read **dprst_frac_init**;

8 = read **stream_tave_init**.

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

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

The PRMS initial conditions file format is specified by control parameter **text_restart_flag** (0 = binary; 1 = text). This file must be created by the same model executable that is used in a restart 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**. Modes PRMS5 executes PRMS only. GSFLOW5 executes integrated MODFLOW-PRMS simulations.

GSFLOW, 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**. Modes `PRMS`, `prms`, `PRMS4`, `prms4`, or `DAILY` executes PRMS only simulations.   `GSFLOW` executes MODFLOW-PRMS integrated simulations.

`MODFLOW` or `modflow` – This mode executes `MODFLOW` only simulations.

`MODSIM-GSFLOW` – This mode executes integrated `MODSIM-MODFLOW-PRMS5` simulations.

`MODSIM-PRMS` – This mode executes integrated `MODSIM-PRMS5` simulations.

`MODSIM` – This mode executes `MODSIM` only simulations.

`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.

RELEASE HISTORY

Version 2.3.0 (March 17, 2023)

This version of GSFLOW is based on MODFLOW-NWT version 1.3.0, MODFLOW-2005 version 1.12.0, and PRMS version 5.3.0. 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.

PRMS Modules

Modifications that are more than simply code formatting are described below.

- Version dates of some modules were updated.
- No changes made to files basin_summary.f90, convert_params.f90, frost_date.f90, gwflow.f90, map_results, muskingum.f90, potet_hamon.f90, potet_hs.f90, potet_jh.f90, potet_pan.f90, potet_pm.f90, potet_pm_sta.f90, potet_pt.f90, precip_dist2.f90, prms_constants.f90, prms_summary.f90, setup_param.f90, strmflow_character.f90, strmflow_in_out.f90, temp_dist2.f90, transp_frost.f90, transp_tindex.f90, write_climate_hru.f90 in the src/prms directory and all except file setup_cont.c in the src/mmf directory.
- Removed all GSFLOW related code from files basin.f90, climateflow.f90, soilzone.f90, subbasin.f90, call_modules.f90, and setup_cont.c.
- Use : instead of 1 as first dimension of two-dimensional arrays passed as arguments to routine as this is more portable between FORTRAN compilers; affected `soltab`, `nhru_summary`, `nsub_summary`, `nsegment_summary`, `glacr_melt`, and `dynamic_param_read`.
- Add error check to be sure value of control parameter **start_time** is before **end_time**.
- To avoid floating-point overflows, snowpack calculations are not made when the snowpack is < 1.0D-12 in `snowcomp`.

- Code to set snow states to 0.0 are consolidated into subroutine set_snow_states_to_zero in `snowcomp`.

BUG FIXES THAT DO NOT AFFECT SIMULATION RESULTS

`climate_hru` and utils_prms.f90
- Removed code associated with reading binary formatted CBH Files when control parameter **cbh_binary_flag** was specified equal to 1 as this option did not work.

temp_1sta_laps.f90
- Module name was printed incorrectly when **temp_module** specified equal to `temp_sta`.

`snowcomp`
- Intrinsic function SNGL used when it should not be to compute *pk_den*.

`water_balance`

Intrinsic function DBLE used when it should not be to compute local variable *hru_in*.

BUG FIXES THAT MAY AFFECT SIMULATION RESULTS

`ddsolrad`
- Added check for divide by zero when *soltab_horad_potsw* or *hru_cossl* are computed equal to 0.0, if so *swrad* is set to 0.0. This condition is extremely rare, perhaps in very northern or southern latitudes with high relief.

`ccsolrad`
- Added check for divide by zero when *soltab_potsw* or *hru_cossl* are computed equal to 0.0, if so *swrad* is set to 0.0. This condition is extremely rare, perhaps in very northern or southern latitudes with high relief.

`climate_hru`, `potet_pm`, `potet_pt`, and `stream_temp`
- Humidity CBH Files were not read. This caused potential evaporation for the Penman-Monteith and Priestly-Taylor to be computed incorrectly. Segment humidity was computed incorrectly when control parameter **strmtemp_humidity_flag** was specified equal to 0 in `stream_temp`.

`muskingum_lake`
- For water use withdrawals from lakes *lake_transfer was subtracted instead of added to lake_outflow*.

`basin_sum`
- Glacier variables *basin_glacrb_melt*, *basin_glacrevap*, and *basin_gl_to_melt* and lake variable *basin_2ndstflow* added to computations.

`nhru_summary`
- Values for the last day of each month were not included to compute mean monthly output (control parameter **nhruOut_freq** specified equal to 4).

`muskingum_mann` and routing.f90

- Stream segment velocity was computed prior to check for **seg_slope** < 0.0000001. A check was added so that if any **seg_slope** values are specified < 0.0000001 they are set to 0.0000001 prior to segment computations. This would have only affected the first computed value.

`dynamic_soil_read_param` (new module with code removed from `dynamic_read_param` that is associated with impervious, surface depression storage, and soilzone dynamic parameters)

- If any *soil_moist* value is updated, *basin_soil_moist* is computed so that the basin water balance is computed correctly when **print_debug** is specified equal to 1.
- If any *slow_stor* value is updated, *ssres_stor* and *basin_ssstor* are computed so that water balances are computed correctly when **print_debug** is specified equal to 1.
- If any surface depression storage (dprst) volume values are updated, *dprst_stor_hru* is computed so that water balances are computed correctly when **print_debug** is specified equal to 1.
- If surface depression storage is > 0.0 and the dynamic surface depression fraction (**dprst_frac**) is specified equal to 0 for an HRU that storage is added to the gravity reservoir instead of capillary reservoir.
- If impervious fraction storage is > 0.0 and the dynamic impervious fraction is specified equal to 0 that storage is added to the gravity reservoir instead of capillary reservoir for any HRU.
- If impervious fraction plus surface depression fraction > 0.999 an error message is printed, and the simulation stops for any HRU.
- If **dprst_frac** specified greater than 0.0 and **dprst_depth_avg** specified equal to 0.0 for an HRU an error message is printed, and the simulation stops.
- If **soil_rechr_max_frac** specified greater than 1.0 it is set to so that *soil_rechr_max* is greater than equal to 0.00001.
- If **soil_moist_max** is specified less than 0.00001 it is set to 0.00001 for any HRU.
- If **soil_rechr_max** is specified less than 0.00001 it is set to 0.00001 for any HRU.

`stream_temp`

- A check was added so that if any **seg_slope** values are specified < 0.0000001 they are set to 0.0000001.
- Set return values *shade* and *svi* to 0.0 when *seg_width* <= 0.000001 for subroutine shday.
- Computation of *seg_tave_lat* is moved before computation of water temperature at the beginning of the time step. This change may lead to significantly different results from previous versions.

`srunoff_smidx` and `srunoff_carea`

- When the soil of an HRU is frozen, surface depression storage (dprst) is assumed to be frozen, thus *dprst_seep_hru*, *dprst_sroff_hru*, and *dprst_evap_hru* are set to 0.0 and all water that would have flowed to dprst is added to *sroff*.

- Check added for the conditions of *snowmelt* = 0.0 and pkwater_equiv = 0.0 and net_snow > 0.0 and *pptmix_nopack* = 1 be sure net_rain isn't added twice. This condition likely does not occur.
- Cascade surface runoff when > CLOSEZERO instead of > 0.0.
- Check for snowpack > 0.0 instead of > DNEARZERO when computing infiltration.
- Check for contributing area fraction < CLOSEZERO, if so set to 0.0.
- Check for pervious surface runoff computed < 0.0, if so set to 0.0.
- Consolidate calculation of water available for surface runoff and infiltration for pervious, impervious, and depression storage to one location. Available water can come from snowmelt, net rain, cascading surface runoff, irrigation application, and glacier melt. Glacier melt was not include is surface-depression storage calculations.

soilzone

- When the soil of an HRU is frozen, water computed flow to the capillary reservoir is added to *sroff*, *hru_sroffp*, *hortonian_flow*, *basin_hortonian*, *basin_sroff*, and *basin_sroffp* instead of added to capillary reservoir storage.
- When the soil of an HRU is frozen, water computed to be Dunnian flow due to infiltration from the land surface is left in preferential flow reservoir storage and water computed to be Dunnian flow due to discharge from the gravity reservoir is left in slow storage.
- Set initial value of ssres_stor = slow_stor + pref_flow_stor as pref_flow_stor could have been set to 0.0 when pref_flow_den = 0.0.
- Check for soil_rechr_max = 0.0 to avoid divide by 0.0.
- If unsatisfied potential evapotranspiration is computed < 0, print warning and set to 0.0.
- Check depth of gravity reservoir to be greater than CLOSEZERO [epsilon(0.0)] to calculate drainage to groundwater storage in GSFLOW mode to reduce chance of floating-point underflow.
- Check that sum of interflow and Dunnian flow is greater than CLOSEZERO [epsilon(0.0)] to calculate cascading interflow and Dunnian flow to reduce chance of floating-point underflow.
- Set cascading interflow and preferential flow to 0.0 if less than CLOSEZERO [epsilon(0.0)] to reduce chance of floating-point underflow.
- Set interflow, preferential flow, and Dunnian flow to 0.0 if less than CLOSEZERO [epsilon(0.0)] to reduce chance of floating-point underflow.
- Set *soil_rechr* to 0.0 if less than CLOSEZERO [epsilon(0.0)] to reduce chance of floating-point underflow.
- If frozen ground leave water that would have been Dunnian flow from excess storage in preferential flow reservoir storage, thus exceeding maximum storage capacity. When ground is no longer frozen the excess storage is released as Dunnian flow.
- When **soilzone_aet_flag** is specified as 1 computation of *soil_rechr* could be computed as a negative value, this is corrected.
- Check for divide by zero when *pref_flow_thrsh* is involved in a division.

NEW FUNCTIONALITY

climate modules: `precip_1sta`, `precip_laps`, `xyz_dist`, `ide_dist`, `precip_map`, `precip_dist2`, `climate_hru`, `temp_1sta`, `temp_laps`, `temp_sta`, `temp_map`, `temp_dist2`

- Added control parameter **forcing_check_flag** that when specified equal to 1 warning checks are made for *hru_ppt* < 0.0, *hru_rain* < 0.0, *hru_snow* < 0.0, *tmax* < *tmin*, *tminf* < -150.0 and *tmaxf* < 200.0. These checks are made in routines precip_form for precipitation values and temp_set for air temperature values with both routines located in climateflow.f90.

`stream_temp` and `obs`

- Added code to read **nstreamtemp** stream temperature values (*stream_temp*) in `obs` that can be used to replace stream temperature for segments identified by **tempIN_segment**.

`stream_temp`

- Code to compute segment width (*seg_width*) was moved to new module `strmflow_character` that also computes *seg_velocity*, *seg_depth*, and *seg_area* based on equations in Moody, J.A. and Troutman, B.M., 2002, Characterization of the spatial variability of channel morphology, Earth Surface Processes and Landforms, DOI 10.1002/esp.403.

`srunoff_smidx` and `srunoff_carea`

- Compute soil-water infiltration to agricultural fractions of each HRU.
- Compute Hortonian flow and contributing area fraction of agricultural areas using routine ag_comp.
- Compute Hortonian flow and infiltration for agricultural areas using routine check_capacity_ag.

`soilzone`

- Added parameter **pref_flow_infil_frac** that is the fraction of infiltration that is partitioned to preferential-flow storage. Previously, **pref_flow_den** set this fraction in addition to the fraction of the gravity reservoir that specifies the water-holding capacity of the preferential-flow reservoir. **pref_flow_infil_frac** defaults to **pref_flow_den**.

utils_prms.f90

- New routine find_cbh_header_end reads a CBH File to the first line that starts with ####, which is based on the find_header_end routine.
- Routine find_header_end was modified to read dynamic parameter, water use, and climate map files to the first line that starts with #### with code related to reading CBH Files removed.

`dynamic_soil_read_param`

- New module to read dynamic parameters and adjust associated states related to impervious, surface depression storage, and soilzone areas. A text file named based on control parameter **dynamic_soil_param_log_file** is generated that summarizes each instance of parameter changes. Code was removed and modified from `dynamic_read_param`.

`snowcomp`
- Merged in simple ground-melt glacier dynamics documented in USGS Open-File Report 02-362 (Mastin, M.C. and Vaccaro, J.J., 2002, Documentation of Precipitation Runoff Modeling System modules for the Modular Modeling System modified for the Watershed and River Systems Management Program.

PARAMETER, DIMENSION, AND VARIABLE CHANGES

New Parameters read from the Control File*:*

forcing_check_flag
- Flag to indicate performance of precipitation and temperature checks (0=no; 1=yes) for *hru_ppt* < 0.0, *hru_rain* < 0.0, *hru_snow* < 0.0, *tmax* < *tmin*, *tminf* < -150.0 and *tmaxf* < 200.0.

dynamic_soil_param_log_file
- Name of file that summarizes each instance of parameter changes read by `dynamic_soil_read_param`.

dyn_ag_frac_flag
- Flag to indicate if a dynamic parameter file that specifies a time series of agricultural fraction (**ag_frac**) of each HRU is required (0=no; 1=yes).

dyn_ag_soil_flag
- Flag to indicate if dynamic parameter files for agricultural capillary soil water capacity (**ag_soil_moist_max** and/or **ag_soil_rechr_max)** that specifies a time series of agricultural fraction of each HRU is required (0=no; 1=yes).

no_snow_flag
- Flag to indicate if snow computations are computed (0=yes; 1=no).

irrigation_apply_flag
- Flag to indicate where to apply irrigation computed by the AG Package (0=off; 1=pervious fraction; 2=canopy; 3=agricultural fraction).

iter_aet_flag
- Flag to indicate to estimate irrigation water based on the difference between actual evapotranspiration and specified actual evapotranspiration; computed in `soilzone_ag` (0=no; 1=yes).

AET_module
- Module to read actual evapotranspiration CBH File; specify climate_hru to activate.

PET_ag_module
- Module to read potential evapotranspiration CBH File; specify climate_hru to activate.

text_restart_flag
- Flag to indicate the format of PRMS initial conditions file (0=binary; 1=text).

seg2hru_flag
- Flag to indicate use of segment_to_hru to apply streamflow to associated HRU (0=no; 1=yes).

xyFileName
- Name of the file that specifies the discretization required to integrate with MODSIM.

mappingFileName

- Name of the file that specifies the discretization required to integrate with MODSIM.

New Dimension and Parameters read from the Parameter File:

nstreamtemp
- Dimension to specify the number of *stream_temp* values specified in the Data File.

tempIN_segment
- Index of streamflow temperature in Data File that replaces temperature in a segment.

depth_alpha
- Alpha coefficient in power function for depth calculation (for units M and CMS)

depth_m
- M value in power function for depth calculation (for units M and CMS)

pref_flow_infil_frac
- Fraction of the soilwater infiltration partitioned to the preferential for each HRU (decimal fraction). If not specified values are set to **pref_flow_den**.

ag_cov_type
- Vegetation cover type for the agricultural fraction.

ag_frac
- Fraction of each HRU area that has agriculture.

ag_soil_moist_max
- Maximum available water holding capacity of the agriculture capillary reservoir.

ag_soil_moist_init_frac
- Initial fraction of available water in the soil agriculture capillary reservoir

ag_soil_rechr_init_frac
- Initial fraction of available water in the agriculture capillary reservoir where losses occur as both evaporation and transpiration.

ag_soil_rechr_max_frac
- Fraction of the agriculture reservoir water-holding capacity (**ag_soil_moist_max**) where losses occur as both evaporation and transpiration.

groundmelt
- Amount of pack-water that melts each day to soils.

Changed Parameters read from the Parameter File:

rain_adj
- Suggested minimum changed from 0.5 to 0.2

snow_adj
- Suggested minimum changed from 0.5 to 0.2 and maximum from 2.5 to 5.0

width_alpha
- Alpha coefficient in power function for segment width calculation based on streamflow in units of cubic meters per second. Suggested minimum, maximum, and default values are 2.6, 20.2, and 7.2 respectively. Previous values were based on streamflow in units of cubic feet per second.

width_m

- M value in power function for segment width calculation based on streamflow in units of cubic meters per second. Suggested minimum, maximum, and default values are 0.48, 0.52, and 0.5, respectively. Previous values were based on streamflow in units of cubic feet per second.

New Variables available for output:
- *seg_depth* – Depth of flow in each segment in units of meters.
- *seg_area* – Cross sectional area of flow in each segment in units of square meters.
- *seg_velocity* – Mean velocity of flow in each segment in units of meters per second.
- *hru_perv_actet* – Actual ET from the capillary reservoir as HRU value in units of inches.
- *stream_temp* – Observed stream temperature values read from Data File.

GSFLOW

For GSFLOW and MODSIM-GSFLOW modes the values variable *hru_storage* are for the land-surface and soilzone water-holding reservoirs. For PRMS5 and PRMS modes it also includes groundwater storage.

`gsflow_prms, gsflow_modflow, intcp, snowcomp, srunoff, soilzone`
- Added control parameter **PRMS_land_iteration_flag** (0=`soilzone` or `soilzone_ag`; 1=[`srunoff_smidx` or `srunoff_carea`] and [`soilzone` or `soilzone_ag`]; 2= [`intcp, snowcomp, glacr_melt, srunoff_smidx` or `srunoff_carea`] and [`soilzone` or `soilzone_ag`]) to allow additional PRMS modules to be included in the MODFLOW iteration loop.
- Most values at the end of the previous time step are saved in "It0_" variables in sm_prms_time.f90 while others are saved in modules where they are first used.

`gsflow_modflow`
- Print Github Commit Hash tag to screen
- Add integration variables for MODSIM simulation modes to argument list with associated code for routines MFNWT_INIT, MFNWT_RUN, SET_STRESS_DATES
- Add interfaces between MODSIM and SFR, MODSIM and AG, and MODSIM and LAK.
- Add interface for `soilzone_ag`.
- Add capability to write rasters of groundwater/surface-water interactions

`gsflow_prms`
- Add interface routine gsflow_prmsSettings to set variables needed to integrate with MODSIM.
- Add integration variables for MODSIM simulation modes to argument list with associated code for routines gsflow_prms, setdims, `gsflow_modsim2prms`, and `gsflow_prms2modsim`.

`gsflow_mf2prms`
- Add capability to transfer water between MODFLOW streams with PRMS surface-depression storage

`gsflow_prms2mf`

- Add capability to transfer water between PRMS surface-depression storage as irrigation based on demands computed by AG Package.
- Add NUZTOP option 5.

`gsflow_budget`

- Check to not set gravity reservoir storage to 0.0 when an HRU is active and the MODFLOW cell is inactive.
- Recompute *basin_dprst_volop* when the AG Package is active.

`gsflow_sum`

- Add setting Stream2Unsat_Q to SFRUZINFIL.

MODFLOW Packages

GSFLOW version 2.3.0 is based on MODFLOW-NWT version 1.3. 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 2.2.1), there has been one MODFLOW-NWT releases (version 1.3). 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, gwf2mnw27_NWT.f, gwf2ag1.f

Unsaturated-Zone Flow (UZF) Package

- A new option was added for specifying the layer to which recharge and discharge occurs. If NUZTOP=5 then recharge is added to the layer specified using IUZFBND and discharge is calculated from the cell corresponding to the highest active layer for each row and column.
- A change was made to how ET is simulated. If EXTDP=0 then ET will not be simulated for these cells. This change was made to allow users to turn off simulation of ET in UZF for selected cells in the model by setting EXTDP=0.

Streamflow Routing (SFR) Package

- An option was added to output formatted outflow for each segment in the SFR network. This option is activated by adding the following line to the SFR input file "Options" block:

    "SEGOUTPUT   Unitsegout"

    Where SEGOUTPUT is a character variable, and Unitsegout is the unit number to which segment outflow will be saved and must match the file unit number specified in the MODFLOW Name file as type "DATA."

Multi-Node Well (MNW2) Package

- A variable was initialized that was not previously.

Agricultural Water Use (AG) Package

- Output written to the cell-by-cell output file was modified to use the three-dimensional output option and to include a unit number to output to a separate output file.
- A new optional character variable was added to the options that allows the user to control nonlinear iteration convergence. If this option is used, GSFLOW will require that changes in the applied irrigation amounts between nonlinear (outer) iterations must be achieved for GSFLOW to converge and move onto the next time step. The convergence tolerance that applies to the change in the volumetric irrigation rate between outer iterations is user specified to the Ag Package input file using the variable AGTOL. Refer to the document called "Input_instructions_AG.pdf" for details.
- A new source of irrigation water from PRMS open surface depression storage reservoirs was added. Water can be diverted from SFR diversion segments to fill reservoirs in the same manner as irrigation segments, where the SFR segment input variable "FLOW" defines the reservoir fill rate. Reservoir irrigation rates can be specified or calculated by the AG Package using the ETDEMAND option. Refer to the document called "Input_instructions_AG.pdf" for details. Information about defining open surface depression storage reservoirs for PRMS is described in Regan and LaFontaine (2017) that is included in this GSFLOW release in the "Related_reports" folder.

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.

This release 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.

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:

$$orad = Swrad(ihru)*Hru\_cossl(ihru)*Soltab\_horad\_potsw(Jday,ihru))/Soltab\_potsw(Jday,ihru)$$
$$cloud\ cover = orad/Soltab\_horad\_potsw(Jday,ihru)$$

- 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.
- c*loud_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, Irestart.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 *scrv*, *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)

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

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

PRMS_iteration_flag

- 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 (CFGI) daily decay of index, value of 1.0 is no decay

cfgi_thrshld – used in frozen ground simulation option

- Continuous frozen ground index (CFGI) 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, Irestart.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 *scrv*, *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)

mbInit_flag

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

stream_temp_shade_flag

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

PRMS_iteration_flag

- 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 (CFGI) daily decay of index, value of 1.0 is no decay

cfgi_thrshld – used in frozen ground simulation option

- Continuous frozen ground index (CFGI) 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, Irestart.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.