Updates for GSFLOW version 1.1.3
February 2011 (updated January 2012; see highlighted text in section 3c)

This file describes modifications made for version 1.1.3 of the GSFLOW code. The initial release of GSFLOW (version 1.0) is documented in Markstrom and others (2008). Version 1.1.3 includes a number of enhancements, modifications, and bug fixes that are summarized in the following sections of this document:

(1) Documentation of the new Grid Report Module for PRMS-only simulations to write PRMS simulated variables in a format compatible with MODFLOW gridded input arrays, such as recharge or infiltration at land surface.

(2) Description of enhanced input options for the PRMS Parameter File.

(3) Additional enhancements and bug fixes to selected GSFLOW and PRMS modules and MODFLOW packages.

(4) Programmer documentation for PRMS and GSFLOW coding changes.

All GSFLOW users should familiarize themselves with the materials described in the first three sections. The issues described in the fourth section are transparent to GSFLOW users but will be of interest to those who want to modify the GSFLOW code.

(1) Grid Report Module

The new PRMS Grid Report Module writes simulated results for each hydrologic response unit (HRU) in a gridded format summarized at three temporal scales—monthly, yearly, and the total simulation time period. The initial release of this module in GSFLOW is currently available for use in PRMS-only mode simulations and only provides for writing PRMS-simulated recharge rates (PRMS output variable `recharge`) from the HRUs to the groundwater reservoirs (GWRs). However, the module is designed such that future versions can write any simulated PRMS and GSFLOW states and fluxes to files of gridded results.

The module allows for interpolation of the recharge rates to the associated MODFLOW cells for each HRU using the topological parameters used to relate HRUs to MODFLOW cells [see table 3, page 27, in the GSFLOW documentation report (Markstrom and others, 2008) for a description of these parameters]. Output files are written in a format that is compatible for use in MODFLOW input files. Additionally, the module can write gridded results based on the identification numbers of the HRUs. In this case, the first value (upper left corner) in the gridded output is HRU 1 and the last value (lower right corner) is from the HRU with identification number `nhru`, the dimension parameter that defines the total number of HRUs.

Variable `recharge` is the sum of PRMS variables `soil_to_gw` and `ssr_to_gw`, as computed within the soilzone_prms module. The calculated flow rates are similar to the potential gravity drainage computed for the first iteration of a GSFLOW time step. The flow rate `soil_to_gw` is based on soil infiltration and cascading surface runoff and interflow and the antecedent storage in the capillary reservoir of each HRU. The flow rate `ssr_to_gw` is computed based on the flow from the capillary reservoir into and antecedent storage within each gravity reservoir (GVR) associated with an HRU. In PRMS-only simulations, the available water to compute `ssr_to_gw` (see equation 59, page 58 in Markstrom and others, 2008) is the same for each associated GVR. In a GSFLOW simulation, the available water in each GVR associated with an HRU can vary due to interactions with the underlying unsaturated and saturated (see page 58 of Markstrom and others, 2008). These interactions include groundwater discharge and rejected potential gravity drainage from the associated MODFLOW cell of the GVR affecting the available water in each GVR. Thus, the potential gravity drainage written by the grid-report module in a PRMS-only simulation will most likely be different than the potential gravity drainage computed during a GSFLOW simulation.

Potential gravity drainage is calculated for each HRU in units of inches/day. Summarized results can be written in units of inches/day, feet/day, centimeters/day, or meters/day, depending on the value specified for parameter `grid_units` (table 1). The gridded results are written to one or more output files as time series of daily rates averaged over the time period(s) selected, as specified by parameter `grid_output_type` (table 1). Results can be written for average monthly rates (output file 'recharge.monthly'), average yearly rates (output file 'recharge.yearly'), and (or) the average rate over the total simulation period (output file 'recharge.total'). The files are written to the directory in which the model is run.

The gridded recharge rates can be used as initial estimates of the infiltration rates at land surface in a MODFLOW simulation (defined using variable `FINF` in the Unsaturated-Zone Flow Package); that is, as initial estimates of recharge to the subsurface zone. Users of MODFLOW and GSFLOW may use the PRMS-determined recharge estimates for calibration purposes for any MODFLOW model. In effect, use of the gridded results produced by the grid-report module is a convenient means to loosely couple PRMS and MODFLOW. Use of PRMS output as recharge input for MODFLOW has been used in various applications (see, for example, Bjerklie and others, in review; Jeton and Maurer, 2007; Steuer and Hunt, 2001; Vaccaro, 1992; and Vaccaro, 2007). GSFLOW users have found these estimates to be useful in the multi-step calibration process in which the PRMS model is calibrated, the grid-report results are used to aide calibration of the MODFLOW model, and then the combined GSFLOW model is calibrated. However, users are cautioned that the recharge rates calculated by PRMS do not reflect interactions with the underlying unsaturated and saturated zones that would be calculated by a full GSFLOW simulation.

The module is activated by setting control parameter `grid_reportON_OFF` to a value of 1 in the GSFLOW Control file by use of the following input structure:

```
####              ← Delimiter
grid_reportON_OFF ← NAME
1                 ← N_VALUES
1                 ← DATA_TYPE
1                 ← VALUE
```

(Note that annotation for each model-input item follows the arrows; this descriptive format is used throughout the document.)

Four new single-value parameters control the grid-report module computations (table 1). The user specifies a warm-up simulation period (control parameter `prms_warmup`; in years) before gridded output is written. Computations begin after the warm-up period. For example, if the simulation start date (control parameter `start_time`) is specified to be 10/1/1980, the end date (control parameter `end_time`) is specified to be 9/30/1996, and `prms_warmup` is specified to be 2, then the grid-report computations will begin on 10/1/1982. For this example, the first monthly results will be for October 1982 and the last monthly results will be for September 1996; yearly results will be for the 14 water years 1983, 1984, and so forth through 1996 (where a water year extends from October 1 of the previous calendar year to September 30 of the water year of interest); and total results will be the average of the 14 water years extending from 10/1/1982 through 9/30/1996. If a user wants results for calendar years, the simulation start time should be specified with a start day of January 1. Results for each time period are preceded by a line that indicates the last day of the averaging period and the mean recharge rate over the basin; results for each time period are followed by a line of #s.

Table 1. Input parameters specified in the Grid Report Module.

Parameter name	Description	Dimension parameter	Units	Type	Range	Default value
`ncol`	Number of columns of the gridded output	`one`	dimensionless	integer	1 to MAX(ngwcell, nhru)	1
`prms_warmup`	Number of years to simulate before computing summary results	`one`	years	integer	0 to (simulation end year - start year)	1
`grid_units`	Flag to specify the output units of summary results (0= inches/day; 1=feet/day; 2= centimeters/day; 3= meters/day)	`one`	dimensionless	integer	0 to 3	0
`grid_output_type`	Flag to specify the frequency of output (0= none; 1=monthly; 2=yearly; 3=total; 4=monthly and yearly; 5=monthly, yearly, and total)	`one`	dimensionless	integer	0-5	1

(2) Enhanced Options for Specifying Input Data for the PRMS Parameter File

Two new options have been added to facilitate data input for the PRMS Parameter File. First, because the Parameter File can become quite large, an option has been added to allow the user to split a single parameter file into multiple files. The option is activated by use of control-parameter item `param_file` in the GSFLOW Control file (see page 134 of Markstrom and others, 2008, for a description of control-parameter items). Previously, only a single parameter file could be specified. The user specifies the number of parameter files using value `N_VALUES` in the control item, as shown in the following example based on the Sagehen test problem in which five parameter files are specified:

```
####                      ← Delimiter
param_file                ← NAME
5                         ← N_VALUES
4                         ← DATA_TYPE
./input/prms.params       ← FILE 1 OF 5
./input/gis.params
./input/gvr.params
./input/ncascade.params
./input/ncascdgw.params   ← FILE 5 OF 5
```

The user can group input parameters in each PRMS Parameter File as desired; however, the first file listed must include the Dimensions declaration section (see pages 142-150 in Markstrom and others, 2008, for a description of the PRMS Parameter File) and the second and all subsequent files must have as their first line the delimiter `####`.

The second option that has been added is the capability to use multiple-value entry in place of individually defined entries for parameter items specified in the PRMS Parameter Files. For example, assume that a watershed has been discretized into 128 HRUs, all of which are land HRUs (that is, `hru_type` = 1). Previous versions of GSFLOW required that 128 values of the land type be entered, one per line, as shown here:

```
####         ← Delimiter
hru_type     ← NAME
1            ← NO_DIMENSIONS
nhru         ← DIMENSION NAME
128          ← N_VALUES
1            ← TYPE
1            ← Value for HRU 1
. . .        ← (126 lines of data deleted here)
1            ← Value for HRU 128
```

With the revised code, the constant 128 land-type values can be entered with a single value using the following parameter item structure:

```
####         ← Delimiter
hru_type     ← NAME
1            ← NO_DIMENSIONS
nhru         ← DIMENSION NAME
128          ← N_VALUES
1            ← TYPE
128*1        ← N_VALUES*VALUE
```

It is also possible to mix multiple and individual entries, as shown for the following partial specification for parameter `covden_sum`:

```
####         ← Delimiter
covden_sum   ← NAME
1            ← NO_DIMENSIONS
Nhru         ← DIMENSION NAME
128          ← N_VALUES
2            ← TYPE
5*1.0        ← First 5 entries
0.9905999898911
```

```
0.9977999925613
. . .       ← (Remaining 121 lines of data deleted here)
```

(3) Modifications to GSFLOW and PRMS Modules and MODFLOW Packages

Several minor modifications and bug fixes were made to some of the GSFLOW and PRMS modules and to three of the MODFLOW Packages, which are described below. Many of these modifications do not affect GSFLOW computations and are therefore transparent to GSFLOW users. Bug fixes made to a couple of the PRMS Modules and MODFLOW Packages resulted in small changes to the output calculated for the Sagehen sample problem and thus may affect results of existing GSFLOW models.

(a) GSFLOW Modules

Computations-Sequence Control Module for PRMS and GSFLOW (gsflow_prms)

Added code to activate the grid_report, climate_vars_prms, and flow_vars_prms modules. Use of the grid_report module is activated by specifying the new control parameter `grid_reportON_OFF` in the GSFLOW Control File to a value of 1. (Modules climate_vars_prms and flow_vars_prms are transparent to the user, and are explained in section 4 of this document.)

BUG FIX: corrected use of the obs_adjust_prms module when using the precip_laps_prms module.

PRMS to MODFLOW Integration Module (gsflow_prms2mf)

The module was modified to allow computation of precipitation and runoff (interflow and overland runoff) to, and evaporation from, a lake simulated by the MODFLOW Lake Package to be based on multiple HRUs. The delineation of HRUs associated with each lake must be coincident with the extent of the MODFLOW grid cells used to define a lake simulated by the Lake Package. That is, the boundary of a lake defined by multiple HRUs must be equal to the boundary of the grid cells that define the MODFLOW lake. This is particularly useful for models that use grid-based HRUs instead of irregular polygon HRUs.

Watershed-Budget Summary Module (gsflow_budget)

BUG FIX: `basin_actet` and `hru_actet` were not being calculated correctly in the GSFLOW budget procedure with regards to lake evaporation.

Flow-Components Summary Module (gsflow_sum)

Added the net cumulative pumping from wells in the CSV file as the second to last column.

Added the precipitation onto and evaporation from lakes in the lake summary values. Precipitation onto and evaporation from lakes are also included in the total basin precipitation and evapotranspiration for the model as reported in the summary table.

(b) PRMS Modules

Cascading-Flow Module (cascade_prms)

An undocumented computation procedure for routing of stream segments and lakes was removed.

Temperature-Distribution Module (temp_1sta_prms)

Note that the purpose of this module is often misunderstood. The module can use measured data from more than one climate station, but only one climate station with a lapse rate is used to compute air temperature for each HRU. Many HRUs can be associated with each climate station, and data for climate stations can be specified in the Data File but not used in the computations. Unused data values in the Data File can be used for other purpose, such as to compare to simulated results.

BUG FIX: Variable `basin_temp` is now set to the units specified by parameter `temp_units`, instead of always having units of Fahrenheit.

Potential Solar-Radiation Module (soltab_hru_prms)

Code was modified to set the minimum potential solar radiation for any day for any HRU to 0.5 langleys. Previous versions of the code would allow values to equal 0.0 langleys; values of 0.0 could cause problems with zero divides. Potential solar radiation can approach zero for north-facing HRUs with very steep slopes during parts of the year, such as during December and January in high-latitude watersheds.

Potential Evapotranspiration Modules (potet_pan_prms and potet_hamon_hru_prms)

BUG FIX: A check was added to the potet_pan_prms module so that when a measured pan evaporation value is missing, the module now uses the measured pan evaporation from the previous time step.

BUG FIX: A check was added to both modules to be sure that if the computed potential evapotranspiration is a negative value, the value is set to 0.0.

Active Transpiration Period Module (transp_tindex_prms)

Code was added to account for the growing season and transpiration time period to span the entire calendar year for any HRU. This change was needed for models developed for the Southern Hemisphere.

Precipitation-Interception Module (intcp_prms)

BUG FIX: the module incorrectly computed the change in storage in the canopy for the days when the season changes from winter to spring or from summer to winter. It is rare that there is storage in the canopy on those two days and the bug fix rarely results in a significant change to simulation results.

Surface Runoff and Infiltration Modules (srunoff_smidx_casc and srunoff_carea_casc)

BUG FIX: a check was added to prevent Hortonian surface runoff from being computed for swale HRUs.

Ground-Water Reservoir Module (gwflow_casc_prms)

This module is only used in PRMS-only simulations.

Two variables were added that can be output to the Statistic Variables and Animation Variables Files. These are: `basin_recharge`, the area-weighted gravity drainage (that is, recharge calculated by PRMS), and `recharge`, the gravity drainage from each HRU.

BUG FIX: A bug fix was made for the computation of the water balance when this module is active. Cascading overland runoff was double-counted and cascading groundwater flow was not included in the basin water-balance computation. This change does not affect simulation results, only the water balance computed when the `print_debug` control parameter is specified to be 1.

BUG FIX: Computations are no longer made for groundwater reservoirs below lake HRUs.

Subbasin Module (subbasin_prms)

This module is intended primarily for PRMS-only simulations to summarize components of streamflow for subbasins within a model for calibration purposes. Also, it can be used to access additional states and fluxes summarized for each subbasin. In some GSFLOW simulations, access to simulated states and fluxes summarized by subbasin has been found to be useful for calibration purposes and perhaps to compare remotely-sensed information such as snow-covered area at the subbasin scale. Therefore, the module is now available for GSFLOW simulations in addition to PRMS-only simulations. However, the user is cautioned that the streamflow and groundwater-discharge values reported for the subbasins do not include components of flow simulated by MODFLOW. The module is made active when the dimension parameter `nsub` is specified to be greater than 0 in the dimension section of the PRMS Parameter File. New computed variables were added that can be output to the Statistic Variables and Animation Variables Files. These variables are area-weighted states and fluxes within each subbasin in units of inches per unit area. The variables are:

subinc_snowcov: subbasin snow-covered area, decimal fraction

subinc_interflow: subbasin interflow, cubic feet per second

subinc_gwflow: subbasin groundwater flow, set to 0.0 for GSFLOW simulations, cubic feet per second

subinc_sroff: subbasin overland flow, cubic feet per second

subinc_pkweqv: subbasin snowpack water equivalent, inches per unit area

subinc_actet: subbasin actual evapotranspiration, inches per unit area

subinc_snowmelt: subbasin snowmelt, inches per unit area

Caution: the following variables, which are streamflow values for water leaving a subbasin, do not include groundwater discharge to or channel routing within the stream network in a GSFLOW simulation and thus are not meant to be used for calibration purposes except in PRMS-only simulations. In a GSFLOW simulation, these variables are the summation of PRMS computed surface-runoff and interflow from HRUs contributing to subbasin streamflow without a base-flow component. These variables are:

sub_inq: the streamflow generated within a subbasin in cubic feet per second

sub_cfs: the streamflow leaving a subbasin that includes upslope subbasin streamflow in units of cubic feet per second sub_cms: the streamflow leaving a subbasin that includes upslope subbasin streamflow in units of cubic meters per second

HRUs Flow-Summary Module (hru_sum_prms)
Code was modified so that computations are only made for active HRUs instead of all HRUs.

(c) MODFLOW Packages

Streamflow-Routing Package (gwf2sfr2.f)

Several updates were made to the SFR2 Package, which are described here. The major changes are described first, and three smaller modifications are described at the end of this section.

Three modifications were made to the SFR2 Package that affect Item 1 of the input file. The modifications are described here, but users should also refer to the SFR2_for_GSFLOW input instructions that accompany this release.

Previous versions of Item 1 had the following data entries:

1. Data: `NSTRM NSS NSFRPAR NPARSEG CONST DLEAK ISTCB1 ISTCB2 {ISFROPT} {NSTRAIL} {ISUZN} {NSFRSETS} {IRTFLG} {NUMTIM} {WEIGHT} {FLWTOL}`

The revised input structure for Item 1 is as follows:

1a. Data: {***REACHINPUT TRANSROUTE***}

1b. Data: {***TABFILES*** NUMTAB MAXVAL}

1c. Data: `NSTRM NSS NSFRPAR NPARSEG CONST DLEAK ISTCB1 ISTCB2 {ISFROPT} {NSTRAIL} {ISUZN} {NSFRSETS} {IRTFLG} {NUMTIM} {WEIGHT} {FLWTOL}`

The two new (optional) keyword variables in Item 1a were added to change the method for invoking the options to specify streambed properties by reach or to simulate unsaturated flow beneath streams (***REACHINPUT***), and to simulate transient streamflow routing (***TRANSROUTE***). Previous versions of SFR2 had used an approach in which a negative value was specified for input variable `NSTRM` to invoke these options. In the new approach, the user specifies keywords ***REACHINPUT*** and (or) ***TRANSROUTE*** as Item 1a, and `NSTRM` must always be specified as a positive value. The definitions of ***REACHINPUT*** and ***TRANSROUTE***, and the revised definition of `NSTRM`, are as follows:

REACHINPUT An optional character variable. When ***REACHINPUT*** is specified, variable `ISFROPT` must be specified in item 1c. `ISFROPT` can be used to change the default format for entering reach and segment data or to specify that unsaturated flow beneath streams will be simulated.

TRANSROUTE An optional character variable that is a flag to indicate that transient streamflow routing is active. When ***TRANSROUTE*** is specified, optional variables IRTFLG, NUMTIM, WEIGHT, and FLWTOL also must be specified in Item 1c.

NSTRM An integer value equal to the number of stream reaches (finite-difference cells) that are active during the simulation.

An updated, complete version of the SFR2 input instructions is provided with the GSFLOW version 1.1.5 release (file 'SFR2_for_GSFLOW_v1.1.5.pdf'). Input data specified using the previous input structure for SFR will be compatible with the updated version, with the exception that if a negative value is specified for NSTRM, the program will stop and an error message will be printed to the MODFLOW LIST file. The user will then need to modify the input file for the updated variables.

Item 1b was added to allow users to specify inflows of water to the first reach of stream segments to be read from files that are external to the SFR2 main input file. Reading specified flow rates from external files allows the user to specify flows that change for each time step, rather than for each stress period. The specified flows must be positive (a negative value for flow can not be specified using an external inflow file). When flows are specified using these files, any flows specified in Item 4a with variable FLOW are ignored.

The external files that contain the specified flows are referred to as tabular flow files. Each tabular file consists of two columns of input that are read using free format: TIME and INFLOW. Time is the point in the simulation when the flow is specified for the segment; INFLOW is the specified flow, in units of length cubed per time. The units for TIME and INFLOW should be consistent with those specified for variables ITMUNI and LENUNI in the MODFLOW (or MODFLOW-NWT) Discretization File. Times listed in the tabular flow file do not need to correspond to the beginning of MODFLOW time steps. If the beginnings of the MODFLOW time steps fall between times listed in the tabular flow file, then the specified inflow is calculated using a time-weighted average of specified flows within the MODFLOW time step. Times can be listed in the tabular flow file either more frequently or less frequently than the MODFLOW time steps.

The option for reading tabular flow files is invoked using the keyword ***TABFILES***, as shown above for Item 1b. Keyword ***TABFILES*** is followed by two integer variables, NUMTAB and MAXVAL. The definitions of these variables are:

TABFILES An optional character variable that is a flag to indicate that inflows to one or more stream segments will be specified with tabular flow files.

NUMTAB An integer value equal to the number of tabular inflow files that will be read if ***TABFILES*** is specified. A separate input file is required for each segment that receives specified flow. Thus, the maximum value of NUMTAB that can be specified is equal to the total number of segments specified with variable NSS in Item 1c.

The name (`Fname`) and unit number (`Nunit`) of each tabular file must be specified in the MODFLOW-2005 Name File using file type (`Ftype`) ***DATA***.

`MAXVAL` An integer value equal to the largest number of rows of specified inflows for any of the tabular flow files. `MAXVAL` is used for memory allocation. For example, if there are two tabular inflow files and the files contain 100 and 200 flow values, respectively, then `MAXVAL` would be specified as 200.

If ***TABFILES*** is specified, then the following variables must be specified *for the first stress period only* after the segment information has been specified (that is, new item 4f). One line of entry is needed for each stream segment for which a time series of flows will be specified (that is, repeat the following line `NUMTAB` times):

Data: `SEGNUM NUMVAL IUNIT`

The definitions of these variables are:

`SEGNUM` An integer value equal to the segment number to which the specified inflows will be applied.

`NUMVAL` An integer value equal to the number of rows in the tabular flow file. Each flow file may contain a different number of rows, but the number of rows in any file cannot exceed `MAXVAL` specified in data Item 1b.

`IUNIT` An integer value equal to the unit number of the tabular inflow file. `IUNIT` must match the unit number for the file specified in the Name File.

The following is part of an example SFR2 input file that demonstrates the ***REACHINPUT*** and ***TABFILES*** functionalities. The example was developed from the 'testsfr2' example that is provided with the MODFLOW-2005 distribution. The example uses one stream segment that consists of 100 reaches:

```
# SFR2 Package input file for hypothetical test simulation
# Example using keyword options
REACHINPUT                                        Item 1a
TABFILES 1 50                                     Item 1b
 100  1  0  0  1.0  0.00001 -1 0 5 10 5 20  0     Item 1c: NSTRM NSS NSFRPAR
NPARSEG CONST DLEAK ISTCB1 ISTCB2 {ISFROPT} {NSTRAIL} {ISUZN} {NSFRSETS}
{IRTFLG}
       1      4      1      1      1   200.0      Item 2
       1      4      2      1      2   200.0
       1      4      3      1      3   200.0
      … (97 lines of input deleted here)
1  0  0 0                                 Item 3: stress period 1
   1 2 0 0  .3 0.0   0.0  0.0 0.030 .04                 Item 4a:
  .00000035 0.5  140.  .3  .1  3.5  6.0e-6              Item 4b:
  .00000035 0.5  110.  .3  .1  3.5  6.0e-6              Item 4c:
0. 2. 4. 6. 8. 10. 12. 14.                              Item 4d:
6.0 4.5 3.5 0. 0.3 3.5 4.5 6.                           Item 4d:
1 50 55                                  Item 4f:   SEGNUM  NUMVAL  IUNIT
```

The tabular flow file has been assigned `IUNIT` 55 and `Fname` ‘testsfr2.tab’ in the Name File:

```
data            55  testsfr2.tab
```

File ‘testsfr2.tab’ has 50 lines of data, the first five of which are:

```
0 0.30            TIME   INFLOW
2592000 2.53
5184000 3.84
7776000 17.85
10368000 20.26
```

The time and inflow values specified in each tabular flow file are echoed to the MODFLOW LIST file.

Three smaller bug fixes also were made to the SFR2 source code for this release:
(1) Changes were made to the code to avoid divide by zero in the subroutines GWFSFR7AD and GWFSFR7FM. (2) A fix was made to the calculation of residual water content for the unsaturated zone beneath stream reaches. The bug only affected simulations with the Block-Centered Flow Package with the option to simulate unsaturated flow beneath streams. (3) A change was made to fix the way stream information was being written to the LIST file.

Lake Package (gwf2lak7.f)

The method for calculating a specified outflow from a lake to a stream was changed. Numerical instabilities occurred in some models when the lake storage was less than the specified outflow to a stream. To fix this problem, the specified outflow calculation was changed to automatically reduce stream outflow to zero over a small interval above the lake bottom using a quadratic smoothing function.

Changes to the source code were made to remove redundant code between “GWFLAK7FM” and “GWFLAK7BD” subroutines for consistency. Calculations of lakebed seepage were removed from these subroutines and put into a new subroutine called "GET_FLOBOT." Subroutine "GET_FLOBOT” is called from the “GWFLAK7FM” and “GWFLAK7BD” subroutines.

All local variables in the Formulate and Budget procedures were declared explicitly and the "IMPLICIT NONE" statement was added. In some cases, variable types were changed from "REAL" to "DOUBLE PRECISION" when a variable was used to calculate derivatives or for calculating budgets.

BUG FIX: Changes to the LAK package were made to correct a bug originally added to the code during the December, 2009 release (MODFLOW-2005 version 1.8; change (5) in "readme_LAK.pdf"). The bug caused the seepage to be calculated incorrectly for some cases when lake cells are disconnected from groundwater.

Unsaturated-Zone Flow Package (gwf2uzf1.f)

A bug was fixed for the calculation of residual water content for the unsaturated zone. The bug only affected simulations with the Block-Centered Flow Package.

A few small additional changes were made to the source code for consistency and efficiency. These changes have no effect on the solution.

(4) Programmer Documentation

The PRMS and GSFLOW modules have been revised to take greater advantage of FORTRAN 95 coding features. These changes have resulted in a substantial reduction in the amount of computer memory required by a simulation and in increased efficiency for a simulation. The primary enhancements are increased use of FORTRAN MODULE structures and the addition of several variables to the modules so that duplicate copies of parameters and simulation variables (states and fluxes computed each time step) could be removed. In addition, single use arrays of parameters and simulation variables are deallocated when no longer needed. Also, increased use of array-assignment statements is done in place of FORTRAN DO LOOPS to increase execution efficiency.

The primary reduction in computer memory involves climate-related arrays and scalar values. For example, memory is allocated in a single module for computed values of air temperature, rain, snow, total precipitation, and solar radiation for each HRU; for basin-wide climate values; and for measured climate values for each climate station, instead of in each module that uses these values for computations. Two such variables, `tmaxf` and `tminf` (the maximum and minimum daily air temperature, respectively, for each HRU) previously were allocated up to four times. Several additional arrays and scalar variables were added to the PRMS basin_prms FORTRAN MODULE. A few of the computed fluxes to or from HRUs are now allocated once in the module flow_vars_prms. The modules climate_vars_prms and flow_vars_prms are included in the file basin_prms.f.

Taking increased advantage of parameters and variables allocated and accessed from the FORTRAN MODULEs has substantially reduced the number of function calls to the MMS utility library, which has resulted in increased execution efficiency. Because the MMS utility library allowed for use of different variable names to refer to the same array of values in any PRMS Module, the naming of arrays was updated to use the same name for all shared array values. Although the use of FORTRAN MODULE variables can be redirected to other local variable names, this feature was not used to maintain consistency of variable names across all PRMS and GSFLOW modules.

Additionally, some shared constant values such as conversion factors, dimensions, and simulation-time variables are set or determined in a single location, which has resulted in more consistent computations. For example, the value used to convert inches per unit area to cubic feet per second was slightly different in one location of the code than in other places. Use of a consistent value throughout the code has resulted in very slight changes to some of the computations. A single routine for conversion of air-temperature units is now used instead of separate routines in each PRMS module that requires conversion of air-temperature units.

Call arguments in the gsflow_prms and gsflow_modflow modules were removed for all PRMS and GSFLOW modules. The use of a flag from the gsflow_prms FORTRAN MODULE indicates the computation process, declare, initialize, run, and cleanup executed by the called module. Another change that affected most PRMS and GSFLOW modules is the replacement of fixed-value dimensions with the actual value. The dimension variables MAXMO and MAXDAY were replaced with the values 12 and 366, respectively.

Additional input-parameter consistency checks were added to catch inconsistent specification of a few parameters in the PRMS Parameter File.

Some modules were updated to avoid the possibility of states and fluxes not being saved correctly for use in a warm-start simulation using the var_save and init_var files, which are specified using the Control File parameters init_vars_from_file, var_init_file, save_vars_to_file, var_save_file (defined in Table A1-1 in Markstrom and others, 2008). For example, a large section of code within the initialize procedure of the soilzone_prms module was reorganized.

The changes described above resulted not only in reductions in memory allocation and improvements in execution efficiency, but also in the elimination of a substantial amount of duplicate code. Most code changes were made in the declare and initialize procedures of the PRMS and GSFLOW modules.

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