Updates for GSFLOW version 1.1.00
November 2009

This file describes modifications to the GSFLOW code that were made for version 1.1.00. The initial release of GSFLOW (version 1.0) is documented in Markstrom and others (2008; http://pubs.usgs.gov/tm/tm6d1/pdf/tm6d1.pdf). Version 1.1.00 includes several changes and bug fixes that are summarized in the following sections of this document: (1) new features, (2) MODFLOW modifications that are relevant to GSFLOW, and (3) modifications to the PRMS and GSFLOW modules. Updated tables from Appendix I of the GSFLOW documentation report are provided in a separate file (Appendix1_Tables_v1.1.pdf); the appendix documents input parameters specified in all PRMS and GSFLOW modules, including two new modules subbasin_prms and obs_adjust_prms. PRMS detention reservoirs have been removed as a simulation option.

New Features in GSFLOW for version 1.1.00

Three new features have been added to GSFLOW for version 1.1.00. These are:

(a) New Hydrologic Response Unit (HRU) types: Two new HRU types were added to PRMS to better coordinate with MODFLOW capabilities. The first is an inactive HRU type, which can be used to make HRUs consistent with underlying inactive MODFLOW cells. Inactive HRUs must be identical in spatial extent to the underlying inactive MODFLOW cells. Thus, an HRU designated as inactive must have all associated MODFLOW cells also designated as inactive. Inactive HRUs are specified using `hru_type` = 0. No computations are made for an inactive HRU from the canopy to the rooting depth; thus, an active MODFLOW cell under an inactive HRU would not receive, or be able to discharge, any flow from the HRU.

The second new HRU type is a swale HRU, which is identical to a land HRU in terms of input parameters and function, except that a swale HRU does not produce cascading surface runoff or interflow to adjacent HRUs or stream segments. A swale HRU should have an average elevation that is lower than or equal to all adjacent HRUs, such as a surface depression or flat area on a valley floor or top of a mesa, such that in a physical sense, lateral flow from the surface or soil zone would not be generated to any adjacent HRU. The underlying MODFLOW cells associated with a swale HRU behave in the normal fashion for any MODFLOW simulation. Swale HRUs are specified using `hru_type` = 3. If an HRU receives cascaded water from upland HRUs but does not cascade to a stream or another HRU, then the `hru_type` for the HRU is automatically assigned a value of 3 to designate it as a swale HRU for the simulation. A warning message is issued by the model when this change is made. It is recommended that the user modify the value of `hru_type` in the PRMS Parameter File for those HRUs that are automatically changed to a swale so that all swale HRUs can be easily identified in the Parameter File. Note that if an HRU that should not be a swale is unexpectedly changed to one, the user may add a cascade link from that HRU to another HRU or stream.

(b) A new PRMS module, Adjusted Observed Data (obs_adjust_prms), has been added to GSFLOW version 1.1. This module is automatically used in a simulation when temperature distribution modules temp_1sta_prms or temp_laps_prms are specified for control parameter temp_module in the GSFLOW Control file. The module checks measured maximum and minimum temperature values to insure that all values are within the range -99.0 and 150.0 degrees. An example of an invalid value is a missing value that would be specified by a large negative value, such as -999. An invalid value is replaced by the last valid value for that measurement station. The module allows the user to specify the maximum number of consecutive invalid values that are allowed for any measurement station, using input parameter max_missing, which is specified in the PRMS Parameter File. When more than max_missing consecutive values are found, the GSFLOW simulation terminates with an error message.

Code for this new module was included in all previously released temperature-distribution modules; the code was removed from these modules, reorganized, and incorporated into this new module. The approach used to detect and adjust invalid temperature values is not appropriate for temperature distribution modules temp_dist2_prms and xyz_dist, because these modules have their own algorithms for handling missing values. Thus, temp_dist2_prms and xyz_dist function as originally designed.

Input parameters for the Adjusted Observed Data Module are described in table A1-9 in the file Appendix_Tables_v1.1.pdf included in this GSFLOW release.

(c) A new PRMS module, Subbasin Computation (subbasin_prms), has been made available for PRMS-only mode simulations using GSFLOW version 1.1. This module computes total surface runoff, interflow, and groundwater flow reaching the stream network within specified groups (subbasins) of hydrologic response units (HRUs). This module provides an additional means for calibrating PRMS-only simulations at internal points of interest in the model domain, such as stream gages and control structures. Calculations are computed in both units of cubic feet per second and cubic meters per second.

The procedure used to compute daily streamflow for any subbasin is the same as that used to calculate streamflow at the outlet of a basin in PRMS-only mode; that is, the sum of all surface runoff, interflow, and groundwater discharge that reaches any stream segment included in the stream network above the outlet of the subbasin equals the outflow of a subbasin for each time step. Thus, the outflow from one subbasin is the sum of outflow from any upstream subbasins plus the flow reaching the stream segments within the subbasin from the HRUs of that subbasin.

Note that the module does not provide streamflow-routing capabilities within each stream segment included in a subbasin; that is, in all cases, inflow to each stream segment is equal to the outflow from each stream segment. However, each subbasin can be calibrated for flow at the outlet of a subbasin, which allows for simple flow routing when the subbasins upstream of another subbasin are calibrated before the downstream subbasin. Thus, when calibrating a PRMS-only model, the most upstream subbasins are calibrated first with the most downstream subbasins calibrated last.

Input parameters to the Subbasin Computations Module specify the HRUs that comprise each subbasin, the downstream order that subbasins are linked together, and the area of each HRU. Each HRU can be assigned to one subbasin using input parameter hru_subbasin. Specifying an hru_subbasin value equal to zero for any active HRU means that the HRU is not included in any subbasin. The downstream order of the subbasins is specified using input parameter subbasin_down. This parameter specifies the subbasin identification number that receives inflow from an upstream subbasin. Specifying a subbasin_down value to zero indicates that this subbasin does not contribute inflow to another subbasin, such as for the outlet subbasin.

Input parameters for the Subbasin Computation Module are described in table A1-21 in the file Appendix_Tables_v1.1.pdf included with this GSFLOW release. Dimension parameter nsub, which is specified in the dimensions section of the PRMS Parameter File, is used to activate the Subbasin Computation Module for a PRMS-only simulation and to define the number of subbasins for the simulation. The number of subbasins that are defined cannot exceed the number of simulated HRUs (that is, nsub must be defined to be less than or equal to dimension parameter nhru). The user has three options for defining nsub:
(1) do not compute subbasin output(s) (nsub = 0);
(2) calculate streamflow at each subbasin outlet (nsub > 0 and <= nhru). In this case, the values specified for parameter hru_subbasin in the PRMS Parameter File designate the HRUs associated with each subbasin. An HRU can only be assigned to one subbasin; or,
(3) calculate streamflow for each HRU (nsub = nhru). In this case, hru_subbasin is a one-to-one correspondence with each HRU identifier.

Note that if nsub has been defined as 0 in the dimensions section of the Parameter File, the parameters subbasin_down and hru_subbasin are ignored if specified.

A variety of output results are computed by the Subbasin Computation Module for flows within a subbasin and total flow leaving a subbasin; the latter includes flow from upstream subbasins. Streamflow and streamflow components (surface runoff, interflow, and groundwater flow) are written for both flows within a subbasin and total flow leaving a subbasin. Additional results for flows within a subbasin include precipitation, snowmelt, evapotranspiration, and snowpack water equivalent.

An example of the use of subbasins is shown in figure 1, which is based on figure 18A in Markstrom and others (2008). There are a total of 21 HRUs and three subbasins. HRU numbers 5-11 are contained within subbasin 1, HRUs 12-18 are contained within subbasin 2, and HRUs 1-4 and 19-21 are contained within subbasin 3. Outflow from subbasins 1 and 2 flows into subbasin 3; consequently input parameter subbasin_down for the Subbasin Computation Module is specified in the PRMS Parameter File to be 3 for subbasins 1 and 2 and 0 for subbasin 3.

The HRU discretization shown in figure 18B in Markstrom and others (2008), which is based on a finite-difference grid of cells coincident with the underlying MODFLOW model, can only be subdivided into a single subbasin or nhru number of subbasins due to complicated divergent flow from the cell-based HRUs. Several HRUs in figure 18B cascade flow to several stream segments. When an HRU (cell or polygon) sends flow to several stream segments, those stream segments and the HRU must be contained within the extent of the subbasin, because an HRU can only be in a single subbasin. Cell-based HRUs are based on the finite-difference computation scheme rather than the topography of the land surface, which is the source of the complicated flow paths from each cell-based HRU shown in figure 18B. Each HRU can only be included in one subbasin, and subbasins are intended to be used for computation of flow at internal points in

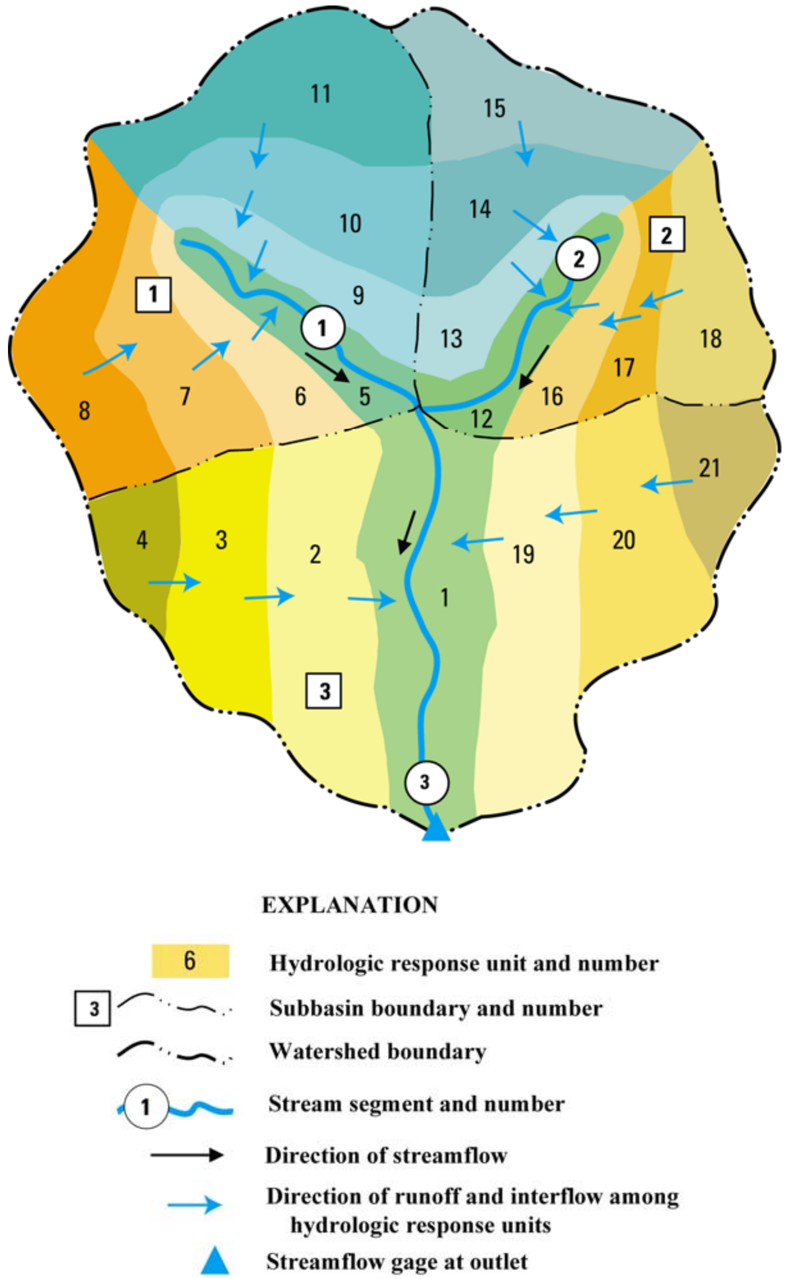

Figure 1. Example use of the PRMS Subbasin Module to delineate a watershed into three sub-basins for a PRMS-only simulation.

a watershed. The discretization in figure 18B does not allow for grouping HRUs in a manner that the sum of the flows produces a meaningful flow except at the watershed outlet.

Subbasin boundaries should be defined such that each HRU included in the subbasin cascades all flow to a single inflow location to a downstream subbasin. Generally, a subbasin should direct all flow through a boundary that is adjacent to a receiving subbasin, or else the outlet of the model domain.

Modifications to MODFLOW

This version of GSFLOW is based on MODFLOW-2005 version 1.7.00. All of the updates to MODFLOW-2005 that have occurred since the initial release of GSFLOW in March 2008 are described in the documents provided with the MODFLOW-2005 distribution available at http://water.usgs.gov/nrp/gwsoftware/modflow2005/modflow2005.html. Users of GSFLOW are encouraged to review all of the relevant documents, starting with the 'release.txt' file provided with the distribution.

In particular, bug fixes and modifications have been made to the Streamflow-Routing (SFR), Lake (LAK), and Unsaturated-Zone Flow (UZF) Packages. For the SFR Package, three new input variables have been added when transient streamflow routing based on the kinematic-wave equation is activated (that is, input variable `IRTFLG` > 0; see Markstrom and others, 2008, p. 68-69 and p. 202-205). Variables `NUMTIM`, `WEIGHT`, and `FLWTOL` follow directly after `IRTFLG` in item 1 of the SFR input-data file:

`NUMTIM`: is the number of sub time steps used to route streamflow. The time step that will be used to route streamflow will be equal to the MODFLOW time step divided by NUMTIM.

`WEIGHT`: is the time weighting factor used to calculate the change in channel storage. WEIGHT has a value between 0.5 and 1. Please refer to equation 83 of Markstrom and others (2008) for further details.

`FLWTOL`: is the streamflow tolerance for convergence of the kinematic wave equation used for transient streamflow routing. A value of 0.00003 cubic meters per second has been used successfully in test simulations (and would need to be converted to whatever units are being used in the particular simulation).

Also, variables `WIDTH1` and `WIDTH2` in the SFR2 Package (pages 208 and 209, Markstrom and others, 2008) were incorrectly defined. These variables should be specified when SFR2 input variable `ICALC` is less than or equal to 1. An additional bug fix made to SFR2 after the release of MODFLOW-2005 version 1.7.00 is relevant for MODFLOW-only simulations with GSFLOW. Runoff generated by the UZF Package was not being added to the assigned stream reaches within the Formulate routine of the SFR2 Package; however, this runoff was being added to stream reaches within the Budget routine, which caused mass balance errors. The bug has been corrected.

Summary of modifications to Parameters in PRMS and GSFLOW

Several PRMS and GSFLOW input parameters were added, removed, or changed for version 1.1.00. Tables in the file Appendix_Tables_v1.1.pdf are updated versions of the tables provided in Appendix 1 of Markstrom and others (2008). Additional tables were added to document input parameters for two new modules: table A1-9 describes input for module obs_adjust_prms and table A1-21 describes input for module subbasin_prms. Table A1-5 lists all parameters that can be defined in the PRMS Parameter File.

One new control parameter was added to the GSFLOW Control File. Parameter print_debug was added to allow for debugging and water-budget checks in many modules. A single integer value is specified for the parameter; see table A1-1 for a complete description of the print_debug options. The most useful values to which print_debug can be set are 1 and 13. For print_debug=1, files with the name of the module with the suffix .wbal are produced for each module that a water-budget check has been computed. These files are found in the directory in which GSFLOW is initiated. Water balances are computed for modules ccsolrad_hru_prms, ddsolrad_hru_prms gsflow_sum, gwflow_casc_prms, intcp_prms, snowcomp_prms, soilzone_prms, srunoff_carea_casc, and srunoff_smidx_casc. For module soilzone_prms, some warning messages about inconsistency of input parameters are only written to the screen when control parameter print_debug=1. Similarly, the file cascade.msgs is produced when print_debug is set to 13. This file contains diagnostics for the process of computing cascade paths among HRUs for all simulation modes, and for groundwater reservoirs for PRMS-only simulations. It is advised that print_debug be set to 13 for initial simulations to review error and warning messages and verify that cascades are computed correctly. Once the cascades are verified, it is advised to set print_debug to 1 to verify that water balances are correct and to review all warning messages.

Modifications to PRMS and GSFLOW modules

Modifications were made to several of the PRMS and GSFLOW modules for version 1.1.00. These modifications can affect model calculations and (or) the content of input and output files. A few general changes were made that affect more than one module. These are:

BUG FIX: A change was made to fix a mass-balance error that resulted from specifying an HRU to be 100 percent impervious (that is, setting hru_percent_imperv equal to 1.0). The maximum allowed percent impervious must now be specified to be less than or equal to 99 percent (that is, setting hru_percent_imperv less than or equal to 0.99). If the user specifies 1.0, hru_percent_imperv is reset to 0.99. This change affects all modules that distinguish between the pervious and impervious areas of HRUs. The basin_prms module checks parameter hru_percent_imperv, makes any necessary adjustments, and then generates variable hru_percent_impv that is used by other modules.

BUG FIX: the computation of cascading order for HRUs and groundwater reservoirs was rewritten to be more general because it was found that in some basin delineations the cascades were computed incorrectly or did not include all HRUs and/or groundwater reservoirs. This involved rewriting a large portion of the Cascade Module.

BUG FIX: GSFLOW models that used temperature-distribution modules temp_dist2_prms or xyz_dist and that had missing values in the PRMS Data File were incorrectly handling use of the missing values. See the Adjusted Observed Data Module description above for more information about this correction.

The remaining changes are described by module in the order in which they appear in the GSFLOW documentation report (Markstrom and others, 2008).

Basin Module (basin_prms)

Parameter `basin_area` is now an optional parameter in the PRMS Parameter File. The area of the basin has always been computed as the sum of the areas of all HRUs, so that a water balance is maintained. The only reason to specify `basin_area` as computed by a process outside GSFLOW (such as using a Geographic Information System), is to verify that the sum of all HRU areas is equivalent to the computed `basin_area` by the other computation process. If they are different, this may indicate a parameter specification problem with your model delineation, or that the delineation process based on a particular Digital Elevation Model (DEM) is different than the value of basin area computed from the other method. The minimum and default values of `basin_area` were changed from 0.01 and 1.0, respectively, to 0.0. The parameter is ignored if the value is 0.0.

Cascade Module (cascade_prms)

Updated code so that groundwater reservoirs (GWRs) can cascade in the same manner as hydrologic response units when `nhru=nhrucell`.

A new parameter (`circle_switch`) was added to turn off checking for circles in the cascade parameters. Checking can take a long time for models with a large number of HRUs. Checking for circles should always be done anytime the cascade parameters are changed. Checking for circles in the cascade should only be turned off after all circles are fixed. Set `circle_switch` to 1 for checking and to 0 to turn off checking for circles.

Cascade warning messages are output to the new cascade_prms.msgs file along with other cascade information in the directory where GSFLOW is initiated when the `print_debug` value is specified as 13, instead of sending the warning messages to the screen. It is recommended that this message file be produced and all warning and error messages addressed prior to making simulations where results are interpreted.

The code now ignores small cascades only when they are less than the area tolerance for cascade links (which is specified with parameter `cascade_tol`) and less than 7.5 percent of the HRU. Previously, small cascades from small HRUs were ignored when only the cascade tolerance criterion was used, which might be inappropriate for models with small HRUs.

Observed Data Module (obs_prms)

If observed streamflow is less than 0.0 in the PRMS Data File, that value is set to -11.0. Users are cautioned not to use the value 0.0 to represent missing data. Missing streamflow data should always be represented by a negative number, such as -999.

Potential Solar-Radiation Module (soltab_hru_prms)

Modified code so that variable `basin_lat` is computed within the module as the area-weighted average for the latitude of each HRU. Previously, `basin_lat` was specified as a parameter in the PRMS Parameter File as the latitude of the basin centroid.

Added computed variable `hemisphere`, which is set based on the value of `basin_lat`. The value of `hemisphere` is a flag set to the hemisphere in which the model resides (0=Northern; 1=Southern).

Temperature Distribution Module (temp_dist2_prms)

Added code to restrict the number of climate stations used to compute the temperature distribution for each HRU. This was added to aid temperature distribution in large models when some measurement stations can be a great distance from an HRU. New parameters were added to allow for this change: dist_max, the maximum distance from an HRU centroid to include a climate station and max_tsta, the maximum number of climate stations to consider for temperature distribution to any HRU.

BUG FIX: code now applies temperature-adjustment factors to computed temperatures for each HRU rather than to each temperature value at each climate station. The adjustment factor was incorrectly added to the temperature distributed to each HRU. This has been corrected so that the adjustment is now subtracted. The parameter name of the adjustment factors were changed from tmin_adj and tmax_adj to tmin_mo_adj and tmax_mo_adj, respectively, as other modules have parameters named tmin_adj and tmax_adj which have a different function.

Precipitation Distribution Modules (precip_prms, precip_laps_prms, and precip_dist2_prms)

(a) precip_prms, precip_laps_prms, and precip_dist2_prms

The code now uses snow adjustment factors for mixed precipitation events.

(b) precip_dist2_prms only

BUG FIX: code now determines the form of precipitation prior to applying precipitation adjustment factors for rain and snow. The form is determined based on the minimum and maximum air temperature of the HRU in comparison with parameter tmax_allsnow and tmax_allrain.

Added code to restrict the number of climate stations used to compute precipitation distributed to each HRU. This was added to aid precipitation distribution in large models. New parameters were added to allow for this change: dist_max, the maximum distance from an HRU centroid to include a climate station and max_psta, the maximum number of climate stations to consider for precipitation distribution to any HRU.

Changed code to use new parameter maxday_prec to set the maximum valid precipitation value instead of using a different value for each month; thus, parameter maxmon_prec is no longer used and was removed from the code.

Solar-Radiation Distribution Modules (ccsolrad_hru_prms and ddsolrad_hru_prms)

Changed hard-coded months for summer (May to September) to depend on Julian Days for March and September Equinox (March 20 and September 22). Summer is March 20 to September 22 in the Northern Hemisphere and September 22 to March 20 in the Southern Hemisphere.

Modules now use solrad_tmax and solrad_tmin (as computed by the air temperature modules) as the maximum and minimmum air temperature at a selected measurement station, which is specified by parameter basin_tsta. This was previously determined in the solar radiation modules. These variables are used to estimate the cloud cover in ccsolrad_hru_prms. This change may slightly affect values for simulated solar radiation and potential evapotranspiration.

Modules now allow for multiple time-series of measured solar-radiation data to be used. Previously, only values for the first time-series specified in the PRMS Data File were used.

BUG FIX: added code to be sure measured solar radiation is valid. If a value is invalid, the solar radiation is computed by the module. Valid values lie between 0.0 and 10,000.0 langleys per day.

BUG FIX: in module ddsolrad_hru_prms, a value in the initial solar table was set to .724 when it should have been .734. This fix could produce a slight change in model results.

Potential Evapotranspiration Modules (potet_hamon_hru_prms, potet_jh_prms, and potet_pan_prms)

BUG FIX: corrected computation of potential evapotranspiration (ET) when transpiration period spans December and January.

Added check in potet_pan_prms for negative (missing) measured values. If a negative measured pan evaporation value is found, it is set to the last non-negative value.

Canopy Interception Module (intcp_prms)

BUG FIX: if storage on winter canopy at changeover from winter to summer with summer cover density = 0.0, then the code now evaporates the storage up to the potential evapotranspiration (ET). If changeover from summer to winter with winter cover density = 0.0, then the code now increases potential ET by the amount of storage in the canopy to maintain the water balance. If either of these conditions is met, then code now updates the basin and HRU potential ET values.

Snow Computation Module (snowcomp_prms)

BUG FIX: based on an updated literature search, the code now uses a different decimal fraction of solar radiation to set the albedo; the code now uses a value of 0.72 instead of 0.81.

Surface Runoff and Infiltration Modules (srunoff_carea_casc and srunoff_smidx_casc)

BUG FIX: evaporation from impervious areas was not being subtracted from the remaining potential evapotranspiration, which was changed. This change fixed a water-balance problem for models with impervious areas.

Soil Zone Module (soilzone_prms)

BUG FIX: because the capillary reservoir only applies to the pervious portion of each HRU, the code was modified such that the amount of available water that flows to the gravity reservoir and drains as groundwater is now based on the pervious area of an HRU. This eliminated double accounting for soil moisture for those HRUs with impervious area. This change meant that the HRU variables `soil_to_gw` and `soil_to_ssr` are computed for the whole HRU rather than only the pervious portion, and basin variables `basin_soil_to_gw` and `basin_soil_to_gw` are computed as the area-weighted average of the whole HRU rather than the area-weighted average of the pervious portion of each HRU. Also, this change affected the code for computing the module water balance when `print_debug` is set to 1.

Added additional warning messages to verify that parameter values are within valid ranges.

Streamflow Module (strmflow_prms)

The code used to simulate flow through surface-detention reservoirs was removed because they are no longer supported in GSFLOW. The module strmflow_prms now does not have any input parameters.

Hydrologic-Response-Unit Summary Module (hru_sum_prms)

Added computation of hru_timestep_outflow_tot, which is the total outflow from an HRU to a stream using variables ssres_flow, gwres_flow, and sroff.

Added cascade variables to compute other components of flow from HRUs, hru_sz_cascade_flow, hru_hortonian_cascadeflow, and hru_gw_cascadeflow. Variable hru_sz_cascade_flow is the cascading flow computed by the soilzone_prms module, which includes interflow and Dunnian runoff. Variable hru_hortonian_cascadeflow is the cascading Hortonian surface runoff computed by the surface runoff module (srunoff_carea_casc or srunoff_smidx_casc). Variable hru_gw_cascadeflow is the cascading groundwater flow computed by the gwflow_casc_prms module, which is only active in PRMS-only mode.

This module is only executed in PRMS-only simulations; thus, it is no longer executed in GSFLOW mode.

Basin Summary Module (basin_sum_prms)

BUG FIX: added parameter outlet_sta, which is used to specify which streamflow gage is the outlet of the basin. The code had previously assumed that the outlet was the gage associated with the first column of measured streamflow in the PRMS Data File.

BUG FIX: if observed streamflow at the basin outlet is negative, the code now sets the observed runoff to 0.0.

Added option to turn off all output from the basin_sum_prms module. To activate this option, set parameters print_freq and print_type to 0.

Added accounting for evaporation from lakes in water-balance computations.

This module is only executed in PRMS-only simulations; thus, it is no longer executed in GSFLOW mode.

GSFLOW Integration Module (gsflow_prms2mf)

Parameter segment_pct_area dimensioned by nreach is no longer used as a parameter. It is now a computed variable dimensioned by nesegment that sets the percentage of flow that each reach receives from the flow entering a segment to a constant. The percentage of segment flow to each reach within a segment is equal to 1 divided by the number of reaches in the segment.

Parameters local_reachid, reach_segment, hru_segment, and numreach_segment are no longer needed, and were removed from the code. They are now determined within the module based on input to the Streamflow Routing (SFR) Package.

BUG FIX: the evaporation on a lake is now set to the remaining evapotranspiration on the HRU (variable hru_actet) instead of the potential evapotranspiration (variable potet) in case other portions of the computed potential evapotranspiration are used in computation of evaporation or sublimation. Currently, lake HRUs cannot have other forms of evaporation, but this might be changed in future GSFLOW versions.

GSFLOW Summary Module (gsflow_sum)

BUG FIX: the variable basin_actet did not include evapotranspiration from lake and swale HRUs. It now accounts for all forms of evapotranspiration.

BUG FIX: the evaporation from lakes is now included in the water-balance check for evapotranspiration (variable basin_lakeevap).

References

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 6-D1, 240 p.