SWAT-MODFLOW Tutorial
Documentation for preparing model simulations
February, 2017

Prepared By:
Seonggyu Park  |  Ryan T. Bailey
envpsg@colostate.edu  |  rtbaily@colostate.edu

Dept. of Civil and Environmental Engineering
Colorado State University

In Association With:
OVERVIEW OF TUTORIAL
This tutorial provides the basic procedure of linking a SWAT model and a MODFLOW model to provide a coupled surface-subsurface hydrologic model. The theory and procedures of coupling the two models is discussed, followed by a step-by-step process of the linking procedure within the context of an example watershed. Necessary files for linking the two models and running the coupled model accompany this document. These files include ArcGIS shapefiles and rasters, SWAT model input files, and MODFLOW input files. This documentation can assist with creating a coupled SWAT-MODFLOW model for a given watershed.

This documentation assumes that SWAT and MODFLOW models have already been constructed for the study area.

TUTORIAL CONTENTS

1. OVERVIEW OF SWAT-MODFLOW
2. OVERVIEW OF LINKING PROCEDURE
3. OVERVIEW OF SWAT-MODFLOW CODE STRUCTURE
4. CREATING THE SWAT-MODFLOW LINKAGE
5. RUNNING THE SWAT-MODFLOW SIMULATION
6. VIEWING RESULTS
7. WATERSHED WATER BALANCE IN SWAT-MODFLOW
8. WATER QUALITY USING SWAT-MODFLOW-RT3D
9. SWATMOD-PREP: GRAPHICAL USER INTERFACE FOR CREATING SWAT-MODFLOW SIMULATIONS
1. Overview of SWAT-MODFLOW

SWAT-MODFLOW is a new coupled hydrologic model that combines the land surface and stream hydrologic processes of SWAT and the groundwater hydrologic processes of MODFLOW to provide a comprehensive coupled hydrologic model for watershed systems. Transport of contaminants in this coupled system also can be simulated by including the RT3D (Reactive Transport in 3 Dimensions) model into the MODFLOW groundwater routines. The inclusion of RT3D is not documented in this tutorial (see Section 8 for more information).

The processes simulated by each model are shown in the following figure. Processes simulated by SWAT are shown with green text, those simulated MODFLOW in blue text, and those simulated by RT3D (if desired) in red text. SWAT performs operations for land surface hydrology, soil hydrology, and surface water hydrology; MODFLOW performs operations for groundwater hydrology and interactions between groundwater and surface water; and RT3D performs operations for solute transport in the aquifer and solute mass exchange between groundwater and surface water.

The remaining sections of this tutorial detail the code structure of SWAT-MODFLOW and the process for linking SWAT features (HRUs, subbasins) with MODFLOW grid cells. A new graphical user interface (SWATMOD-Prep) for facilitating the preparation of SWAT-MODFLOW simulations is described in Section 9. However, a detailed tutorial for SWATMOD-Prep has also been developed and is available on the SWAT-MODFLOW website (http://swat.tamu.edu/software/swat-modflow/).
2. Overview of Linking Procedure

Running a coupled SWAT-MODFLOW model requires that values of state variables be passed ("mapped") from the SWAT model to the MODFLOW model and from the MODFLOW model back to the SWAT model. The following state variables are passed between the two models:

- Soil deep percolation (from SWAT HRUs to MODFLOW grid cells)
- Subbasin stream stage (from SWAT subbasins to MODFLOW river cells)
- Groundwater discharge (from MODFLOW river cells to SWAT subbasins)
- Water table elevation (from MODFLOW grid cells to SWAT HRUs)

As SWAT HRUs do not have a designated geographic location, HRUs are disaggregated in pre-processing GIS routines. Disaggregation splits apart an HRU into individual polygons that have a specific geographic location. These Disaggregated HRUs (DHRUs) are then intersected with MODFLOW grid cells in order to pass variables between SWAT and MODFLOW. Also, MODFLOW River Cells, for which volumetric flow exchange rates between the aquifer and the stream are estimated, are intersected with SWAT subbasins for transferring groundwater return flow rates to the correct subbasin stream. The following figure shows a MODFLOW grid (16 rows, 21 columns) and a SWAT subbasin with 4 HRUs (each in a different color). HRU #4 can be split apart to create 3 DHRUs, each with a specific geographic location. These DHRUs then are intersected with the MODFLOW grid, with the resulting weighted areas used to pass information between SWAT and MODFLOW. The subbasin also contains 19 MODFLOW River Cells (shaded in blue). These River Cells will be linked with the subbasin, so that volumetric flow rates of groundwater return flows to the stream will be given to this subbasin in the watershed.
3. Overview of SWAT-MODFLOW Code Structure

Both SWAT and MODFLOW are written in the FORTRAN programming language. The MODFLOW model is called as a subroutine within the SWAT code. It replaces the original SWAT groundwater subroutines, and hence these subroutines are not active when MODFLOW is being used. By default, the MODFLOW model is called daily. However, any frequency can be specified in the `swatmf_link.txt` file (see next section). The following figure shows the structure of the code. Within the daily SWAT loop, all subbasins calculations are performed first, followed by mapping variables to the MODFLOW grid cell, running MODFLOW, and then mapping variables back to SWAT. Routing of surface return flow and groundwater return flow through the watershed stream network then can be performed for that day.

**SWAT-MODFLOW Code Structure**

- Read/Allocate SWAT arrays
- Read/Allocate MODFLOW arrays
- Read SWAT-MODFLOW linkage files

**Simulate**

**Year Loop**

**Day Loop**

command:

- Subbasin (HRU) calculations
- MODFLOW

1. Map SWAT → MODFLOW Grid Cells
   - SWAT HRU values → disaggregated HRUs (DHRUs)
   - Recharge
   - SWAT DHRUs → Grid cells
   - SWAT channel depth → MODFLOW River cells

2. Run MODFLOW

3. Map Grid → SWAT
   - Aquifer-stream interactions → SWAT subbasin streams
   - Route water through SWAT subbasin channels
4. Creating the SWAT-MODFLOW Linkage

The information required to link HRUs, DHRUs, SWAT subbasins, and MODFLOW grid cells is contained in 4 text files that are read in at the beginning of the SWAT-MODFLOW simulation. These text files are:

1. `swatmf_dhru2hru.txt` (relates HRUs to DHRUs)
2. `swatmf_dhru2grid.txt` (relates DHRUs to Grid Cells)
3. `swatmf_grid2dhru.txt` (relates Grid Cells to DHRUs)
4. `swatmf_river2grid.txt` (relates River Cells to Subbasins)

The linkage information is stored in memory during the simulation and used when variables are passed between the two models. The process of creating each of the 4 text files is as follows:

1. Perform basic intersection/extraction routines in a GIS
2. Prepare tables that contain results of the GIS routines
3. Run a FORTRAN program that creates the 4 SWAT-MODFLOW input files

This process is now described in more detail. Example tables and SWAT-MODFLOW input files are provided with this documentation.
4.1 Linking Procedure Using ArcGIS Routines

This section describes the process to link SWAT features (HRUs, subbasins) with the MODFLOW grid cells. The files used in this process are contained in the folder “Workshop Materials\Example Simulation – LRW”, which contains all files necessary to create a SWAT-MODFLOW model for the Little River Watershed near Tifton, Georgia. The files are contained in the following 6 sub-folders:

- The 1st folder contains the SWAT model input files and the SWAT shape files (HRU, River, Subbasin).
- The 2nd folder contains the MODFLOW simulation input files.
- The 3rd folder contains the 4 linking tables that will be created using GIS routines. These files are placed here for your convenience. The process of creating these files is described in this section.
- The 4th folder contains files necessary for running a SWAT-MODFLOW simulation.
- The 5th folder contains files for viewing results of a SWAT-MODFLOW simulation.
- The 6th folder contains files for running a SWAT-MODFLOW-RT3D simulation.

In the following procedures, the following two symbols are use frequently:

- : Left click
- : Right click
4.1.1 Linkage between HRUs and Disaggregated HRUs (DHRUs)

File to create: **hru_dhu**. This file has the following structure:

**At the top of the file:**

- *Number of DHRUs*
- *Number of HRUs*

**Then, the following columns:**

- **dhru_id**: ID of DHRU (sequential numbering)
- **dhru_area**: Spatial Area \( (\text{m}^2) \) of the DHRU
- **hru_id**: ID of the HRU from which the DHRU originates
- **subbasin**: ID of the Subbasin
- **hru_area**: Spatial area \( (\text{m}^2) \) of the original HRU

For example:

<table>
<thead>
<tr>
<th></th>
<th>dhru_id</th>
<th>dhru_area</th>
<th>hru_id</th>
<th>subbasin</th>
<th>hru_area</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>27396</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>6233</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td>dhru_area</td>
<td>hru_id</td>
<td>subbasin</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>9000</td>
<td>1</td>
<td>1</td>
<td>153000</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>900</td>
<td>1</td>
<td>1</td>
<td>153000</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>900</td>
<td>1</td>
<td>1</td>
<td>153000</td>
</tr>
<tr>
<td>7</td>
<td>4</td>
<td>900</td>
<td>1</td>
<td>1</td>
<td>153000</td>
</tr>
<tr>
<td>8</td>
<td>5</td>
<td>45500</td>
<td>1</td>
<td>1</td>
<td>153000</td>
</tr>
<tr>
<td>9</td>
<td>6</td>
<td>89100</td>
<td>1</td>
<td>1</td>
<td>153000</td>
</tr>
<tr>
<td>10</td>
<td>7</td>
<td>7200</td>
<td>1</td>
<td>1</td>
<td>153000</td>
</tr>
<tr>
<td>11</td>
<td>8</td>
<td>900</td>
<td>2</td>
<td>1</td>
<td>7200</td>
</tr>
<tr>
<td>12</td>
<td>9</td>
<td>900</td>
<td>2</td>
<td>1</td>
<td>7200</td>
</tr>
<tr>
<td>13</td>
<td>10</td>
<td>900</td>
<td>2</td>
<td>1</td>
<td>7200</td>
</tr>
<tr>
<td>14</td>
<td>11</td>
<td>900</td>
<td>2</td>
<td>1</td>
<td>7200</td>
</tr>
<tr>
<td>15</td>
<td>12</td>
<td>1800</td>
<td>2</td>
<td>1</td>
<td>7200</td>
</tr>
<tr>
<td>16</td>
<td>13</td>
<td>1800</td>
<td>2</td>
<td>1</td>
<td>7200</td>
</tr>
<tr>
<td>17</td>
<td>14</td>
<td>54000</td>
<td>3</td>
<td>1</td>
<td>791100</td>
</tr>
<tr>
<td>18</td>
<td>15</td>
<td>423000</td>
<td>3</td>
<td>1</td>
<td>791100</td>
</tr>
<tr>
<td>19</td>
<td>16</td>
<td>900</td>
<td>3</td>
<td>1</td>
<td>791100</td>
</tr>
<tr>
<td>20</td>
<td>17</td>
<td>900</td>
<td>3</td>
<td>1</td>
<td>791100</td>
</tr>
<tr>
<td>21</td>
<td>18</td>
<td>63000</td>
<td>3</td>
<td>1</td>
<td>791100</td>
</tr>
<tr>
<td>22</td>
<td>19</td>
<td>54000</td>
<td>3</td>
<td>1</td>
<td>791100</td>
</tr>
<tr>
<td>23</td>
<td>20</td>
<td>1800</td>
<td>3</td>
<td>1</td>
<td>791100</td>
</tr>
<tr>
<td>24</td>
<td>21</td>
<td>900</td>
<td>3</td>
<td>1</td>
<td>791100</td>
</tr>
<tr>
<td>25</td>
<td>22</td>
<td>900</td>
<td>3</td>
<td>1</td>
<td>791100</td>
</tr>
<tr>
<td>26</td>
<td>23</td>
<td>900</td>
<td>3</td>
<td>1</td>
<td>791100</td>
</tr>
<tr>
<td>27</td>
<td>24</td>
<td>900</td>
<td>3</td>
<td>1</td>
<td>791100</td>
</tr>
<tr>
<td>28</td>
<td>25</td>
<td>225900</td>
<td>3</td>
<td>1</td>
<td>791100</td>
</tr>
<tr>
<td>29</td>
<td>26</td>
<td>1800</td>
<td>3</td>
<td>1</td>
<td>791100</td>
</tr>
<tr>
<td>30</td>
<td>27</td>
<td>9900</td>
<td>3</td>
<td>1</td>
<td>791100</td>
</tr>
<tr>
<td>31</td>
<td>28</td>
<td>2700</td>
<td>4</td>
<td>1</td>
<td>2700</td>
</tr>
</tbody>
</table>
1. Begin with HRU shapefile (no thresholds)

① Import the “hru1” shapefile (1 SWAT LRW folder) into ArcMap
② Add the spatial area (m²) of the HRUs in the “hru_area” field
2. Apply the GIS operation "Multipart to Singlepart" to create the DHRU shape file

① Open “Multipart to Singlepart” tool

- Run "Multipart to Singlepart" tool

- Choose hru1 as input features

- Specify a directory to save the “hru_d” shapefile

- The “hru_d” shapefile will be added.
3. Get Area, unique ID, and subbasin for each DHRU

① Open the attribute table of the “hru_d” shapefile

② Create “dhru_id” field with long integer type
③ Create IDs for the DHRUs in a spreadsheet of Excel. *It is important that the HRUs are sorted by ID before providing IDs to each DHRU. This will be described in this step.*
- Paste the IDs of DHRU copied from the spreadsheet into "dhru_id" field
  * First, check the attribute table of hru_dhru shapefile is sorted by HRU_ID

- Save the edited hru_d shapefile
  (Activate Editor tool)
④ Create “dhru_area” field with float type

- Type dhru_area in Name
- Change Type to Float

- Calculate the spatial areas (m²) of the DHURUs
- Change Property to Area
- Change Unit to square meters

- dhru_area
⑤ Intersect the “hru_d” with the “sub1” shapefile
- Run Intersect tool

- Add the “sub1” and “hru_d” shapefiles in Input Features
- Specify the output feature class name (hru_dhru) and directory
⑥ Select only the necessary fields (You can either turn off or delete an unnecessary field)
⑦ Provide text file: hru_dhru (This file is sorted by the HRU and DHRU IDs)
- Use Filter and Sort HRU_ID column in ascending order

- Change the order of the columns and correct the column names

- Insert two rows at the top of the spreadsheet and write the numbers of DHRUs in 1st and HRUs in 2nd row

- Save the spreadsheet as "hru_dhru" with text file format

- Reduce the number of digits after decimal point if desired
4.1.2 Linkage between DHRUs and MODFLOW Grid cells

File to create: **dhru_grid**. This file has the following structure:

At the top of the file:

- **Number of lines with information (starting on Line 4)**
- **Number of MODFLOW grid cells**

Then, the following columns (sorted by **grid_id**, then by **dhru_id**):

- **grid_id**: ID of the MODFLOW grid cell (only cells intersecting DHRUs)
- **grid_area**: Spatial Area (m²) of the grid cell
- **dhru_id**: ID of the DHRU
- **overlap_area**: Overlap area (m²) between the cell and the DHRU
- **dhru_area**: Spatial area (m²) of the DHRU

For example:

```
1 61838
2 19176
3 grid_id grid_area dhru_id overlap_area dhru_area
4 16 40000 27 9000 9000
5 16 40000 58 600 900
6 16 40000 63 1900 31500
7 17 40000 7 6000 7200
8 17 40000 27 6500 9000
9 17 40000 57 600 4500
10 17 40000 58 600 900
11 17 40000 63 800 31500
12 18 40000 57 400 4500
13 137 40000 1158 5600 78500
14 138 40000 1158 25100 76500
15 138 40000 1158 4500 11700
16 139 40000 1158 6600 75500
17 139 40000 1158 3300 272700
18 139 40000 1388 4200 9000
19 140 40000 1159 1400 272700
20 141 40000 1159 8300 272700
21 142 40000 1146 900 900
22 142 40000 1159 21300 272700
23 142 40000 1251 300 53100
24 143 40000 1145 900 900
25 143 40000 1146 900 900
26 143 40000 1155 3200 68400
27 143 40000 1159 900 272700
28 143 40000 1251 1500 53100
29 144 40000 1147 2700 5400
30 144 40000 1155 400 68400
31 144 40000 1156 900 900
32 144 40000 1157 700 7200
33 144 40000 1159 900 272700
34 145 40000 2356 1800 290700
35 145 40000 1147 2700 5400
36 145 40000 1157 1700 7200
37 152 40000 63 1100 31500
```
1. Create MODFLOW shapefile

① Create a fishnet of rectangular cells as MODFLOW Grid cells
② Generate IDs of the MODFLOW grid cell (The origin of MODFLOW grid starts at upper left corner)
- Open the “Polygon to Raster” tool

- Select “dhru_g” for input features
- Choose the “FID” for value field
- Specify your directory
- Name “dhru_grid” for output Raster Dataset
- Select “CELL_CENTER”
- Select “NONE”
- Type your MODFLOW grid cell size

- New model is shown in the Table Of Contents.
- Open the "Raster to Polygon" tool

- Select "dhru_grid" for input raster
- Choose the "VALUE" for Field
- Specify your directory
- Name "dhru_gr" for output polygon features
- Open the attribute table of the “dhru_gr” shapefile.

- Click “FID 0” and see where it starts.
  The origin of the “dhru_gr” shapefile starts at the upper left corner.

- Clear selected features.

- (Images showing the attribute table with selected features and cleared features.)
- Create the "grid_id" field with "long integer" type ("ID" field can be used for "grid_id" field and edit the field name in Excel)

- Use Field Calculator to generate values for "grid_id" field

then click "OK"
③ Calculate the spatial area of the grid cell
2. Intersect the “dhru_gr” shapefile with “hru_dhru” shapefile

① Intersect the “dhru_gr” shapefile with “hru_dhru” shapefile
② Calculate the overlap area between Grid cells and DHRUs

- Create the “overlap_area” field with the “Float” type

- Type “overlap_area” in Name
- Change Type to Float

* Warning will be shown as the following figure. Click “Yes”. The name will be edited with Excel later.
- Calculate the overlap area between Grid cells and DRHUs

- Set Property to “Area” & Units “Square Meters”
③ Select only the necessary fields (You can either turn off or delete an unnecessary field)
4. Provide text file: **dhru_grid** (This file is sorted by the “grid_id”, then by “dhru_id”)

- Export the attribute table of the “dhru_grid” shapefile as dBASE table (*.dbf)

- Change Type to dBASE Table

- Specify the output table name (dhru_grid_db) and directory

- Open the “dhru_grid_db” file with Excel
- Use Filter and Sort the "grid_id" column in ascending order.

- Change the order of the columns and correct the column names.

- Insert two rows at the top of the spreadsheet and write the number of lines with information (starting on Line 4) and number of MODFLOW grid cells.

- Save the spreadsheet as text file format.

- Reduce the number of digits after decimal point if desired.
4.1.3 Linkage between DHRUs and MODFLOW Grid cells (sorted by dhru_id)

File to create: grid_dhru. The same content as in dhru_grid, except sorted by dhru_id, then by grid_id. Also, the following information is needed at the beginning of the file:

At the top of the file:

- Number of lines with information (starting on Line 6)
- Number of DHRUs
- Number of rows (in the MODFLOW grid)
- Number of columns (in the MODFLOW grid)

For example:

```
1 61838
2 27396
3 141
4 136
5 grid_id grid_area  dhru_id overlap_area  dhru_area
6  702   40000   1    4500    9000
7  838   40000   1    4500    9000
8  702   40000   2    900     900
9  702   40000   3    900     900
10 568   40000   4    900     900
11 425   40000   5    9800    45900
12 425   40000   5    10900   45900
13 561   40000   5    15100   45900
14 562   40000   5    10100   45900
15 291   40000   6    16500   89100
16 292   40000   6    3300    89100
17 427   40000   6    7200    89100
18 426   40000   6    30300   89100
19 429   40000   6    14400   89100
20 565   40000   6    16000   89100
21 761   40000   6    6900    89100
22 17    40000   7    6000    7200
23 153   40000   7    1200    7200
24 838   40000   8    900     900
25 564   40000   9    900     900
26 427   40000  10    900     900
27 291   40000  11    900     900
28 291   40000  12    1800    1800
29 153   40000  13    1800    1800
30 973   40000  14    6500    54000
31 1108  40000  14    2400    54000
32 1109  40000  14    24300   54000
33 1244  40000  14    5100    54000
34 1245  40000  14    15600   54000
35 563   40000  15    1700    42300
36 564   40000  15    2200    42300
37 694   40000  15    2400    42300
38 695   40000  15    14700   42300
39 696   40000  15    14100   42300
```
① Provide text file: `grid_dhru` (This file is sorted by the “dhru_id”, then by “grid_id”)

- Sort the “dhru_id” column in ascending order

- Insert two more rows above the row with the names of the columns

- Keep the value in 1st row, change the value to the number of DHRU in 2nd row, add the number of rows (in the MODFLOW grid) in 3rd row, and the number of columns (in the MODFLOW grid) in 4th row.

- Save the spreadsheet as the text file format
4.1.4 Linkage between MODFLOW River Cells and Subbasins

File to create: `river_grid`.

At the top of the file:

*Number of lines with information (starting on Line 3)*

Then, the following columns (sorted by grid column, then by grid row):

- `grid_id`: ID of the MODFLOW grid cell
- `subbasin`: ID of the Subbasin
- `rgrid_len`: Length of the stream in the grid cell

Note: the SWAT-MODFLOW code uses the `grid_id` of each cell to link with River Cells specified in the MODFLOW River package. The code matches this `grid_id` and the ID of the River Cells to provide groundwater return flow rates to the correct SWAT subbasin.

For example:

```
1 1921
2 grid_id subbasin rgrid_len
3 564  1     197.78200000000
4 565  1     198.78000000000
5 781  1     283.13700000000
6 782  1     42.42640000000
7 826  9     7.07105000000
8 821  9     164.85300000000
9 838  1     123.64000000000
10 838 57     151.92400000000
11 957  9     100.71100000000
12 956  9     255.76000000000
13 974 57     40.35500000000
14 975 57     277.65300000000
15 966 57     102.78200000000
16 1059 9     26.28400000000
17 1055 9     287.59000000000
18 1056 9     14.12100000000
19 1056 17  153.64000000000
20 1112 57     215.20800000000
21 1113 57     114.85300000000
22 1232 9     257.99000000000
23 1234 17  245.56300000000
24 1249 57     173.13700000000
25 1250 57     245.56300000000
26 1251 57     162.67100000000
27 1368 9     60.35530000000
28 1369 9     217.27900000000
29 1371 49     35.35530000000
30 1371 25     55.60000000000
31 1371 17     262.63500000000
32 1372 25     115.85300000000
```
1. Compute SWAT stream network in the MODFLOW Grid

① Calculate each length of the stream in each grid cell
- Open "Identity" tool

Select "riv1" for Input Features
Select "dhru_gr" for Identity Features
Specify your directory
Name "river_grid" for output feature class

Keep relationships (optional)
Uncheck
- Create the "rgrid_len" field with the "Float" type

- Type "rgrid_len" in Name
- Change Type to Float
- Calculate the length of the streams in each grid cell

- Set Property to “Length” & Units “Meters”

<table>
<thead>
<tr>
<th>MinE</th>
<th>MaxE</th>
<th>Shape_Leng</th>
<th>HydroID</th>
<th>OutletID</th>
<th>FID_dthru_g</th>
<th>ID</th>
<th>GRIDCODE</th>
<th>grid_id</th>
<th>grid_area</th>
<th>rgrid_len</th>
</tr>
</thead>
<tbody>
<tr>
<td>118.375639</td>
<td>124.365331</td>
<td>116.969965</td>
<td>200001</td>
<td>100001</td>
<td>1370</td>
<td>137</td>
<td>17690</td>
<td>1371</td>
<td>40000</td>
<td>35.3553</td>
</tr>
<tr>
<td>118.375639</td>
<td>124.365331</td>
<td>116.969965</td>
<td>200001</td>
<td>100001</td>
<td>1507</td>
<td>159</td>
<td>17555</td>
<td>1508</td>
<td>40000</td>
<td>218.777</td>
</tr>
<tr>
<td>118.375639</td>
<td>124.365331</td>
<td>116.969965</td>
<td>200001</td>
<td>100001</td>
<td>1643</td>
<td>164</td>
<td>17419</td>
<td>1644</td>
<td>40000</td>
<td>212.426</td>
</tr>
<tr>
<td>118.375639</td>
<td>124.365331</td>
<td>116.969965</td>
<td>200001</td>
<td>100001</td>
<td>1779</td>
<td>176</td>
<td>17283</td>
<td>1780</td>
<td>40000</td>
<td>247.635</td>
</tr>
<tr>
<td>118.375639</td>
<td>124.365331</td>
<td>116.969965</td>
<td>200001</td>
<td>100001</td>
<td>1915</td>
<td>191</td>
<td>17147</td>
<td>1916</td>
<td>40000</td>
<td>220.711</td>
</tr>
<tr>
<td>118.375639</td>
<td>124.365331</td>
<td>116.969965</td>
<td>200001</td>
<td>100001</td>
<td>2051</td>
<td>205</td>
<td>17011</td>
<td>2052</td>
<td>40000</td>
<td>186.068</td>
</tr>
<tr>
<td>118.375639</td>
<td>124.365331</td>
<td>116.969965</td>
<td>200001</td>
<td>100001</td>
<td>1915</td>
<td>191</td>
<td>17147</td>
<td>1916</td>
<td>40000</td>
<td>220.711</td>
</tr>
<tr>
<td>118.375639</td>
<td>124.365331</td>
<td>116.969965</td>
<td>200001</td>
<td>100001</td>
<td>2051</td>
<td>205</td>
<td>17011</td>
<td>2052</td>
<td>40000</td>
<td>186.068</td>
</tr>
<tr>
<td>118.375639</td>
<td>124.365331</td>
<td>116.969965</td>
<td>200001</td>
<td>100001</td>
<td>1915</td>
<td>191</td>
<td>17147</td>
<td>1916</td>
<td>40000</td>
<td>220.711</td>
</tr>
<tr>
<td>118.375639</td>
<td>124.365331</td>
<td>116.969965</td>
<td>200001</td>
<td>100001</td>
<td>2051</td>
<td>205</td>
<td>17011</td>
<td>2052</td>
<td>40000</td>
<td>186.068</td>
</tr>
</tbody>
</table>
② Select only the necessary fields (You can either turn off or delete unnecessary fields)

Using these arrow buttons, you can change the order.

Then, click OK.
③ Provide text file: river_grid

- Export the attribute table of the "river_grid" shapefile as dBASE table (*.dbf)

- Change Type to dBASE Table

- Specify the output table name (river_grid.db) and directory

- Open the "river_grid.db" file with Excel
- Use Filter and Sort the “grid_id” column in ascending order.
- Change the order of the columns and correct the column names.
- Insert one row at the top of the spreadsheet and write the number of lines with information (starting on Line 3).
- Reduce the number of digits after decimal point if desired.

- Save the spreadsheet as text file format.
4.2 CREATE SWAT-MODFLOW INPUT FILES

Now that the four linkage files have been created, the four SWAT-MODFLOW text input files can be created:

1. Place the hru_dhru.txt, dhru_grid.txt, grid_dhru.txt, and river_grid.txt files into the folder with the CreateSWATMF.exe FORTRAN program. Before running, make sure that the .txt extensions are deleted for each of the files.

2. Run CreateSWATMF.exe. Even for large watersheds with thousands of HRUs and MODFLOW grid cells, this program should only take 10-30 seconds to run. This will create the following files:

   - swatmf_dhru2hru.txt
   - swatmf_dhru2grid.txt
   - swatmf_grid2dhru.txt
   - swatmf_river2grid.txt
3. Create the `swatmf_link.txt` file (see example file in the “Example Simulation - LRW\4 SWAT MODFLOW LRW” folder). This text file contains basic information for the SWAT-MODFLOW simulation:

   i. Flag for including MODFLOW (0 or 1)
   
   ii. Flag for including RT3D (0 or 1) (for RT3D linkage, see Section 8)
   
   iii. Frequency of MODFLOW runs (# of days between MODFLOW calls)
   
   iv. Flag for reading observation cells (observation file was created). If desired, a `modflow.obs` file can be created. This file contains indices (I,J,K) for grid cells for which groundwater head data will be output for each time step. An example file is located in the “Example Simulation - LRW\2 MODFLOW LRW\MODFLOW model” folder.
   
   v. Flags for optional model output (0 or 1)
5. RUNNING THE SWAT-MODFLOW SIMULATION

5.1 Place the following files in the folder containing the original SWAT model:

- MODFLOW input files. Be sure to set your MODFLOW model to transient mode within the discretization file (*.dis):

- MODFLOW name file (change name to modflow.mfn). Within the name file, add 5,000 to each file identification integer. This is done so that file integers do not conflict with SWAT input/output files.
- SWATMF\_link.txt
- Mapping files:
  - SWATMF\_dhru2hru.txt
  - SWATMF\_dhru2grid.txt
  - SWATMF\_grid2dhru.txt
  - SWATMF\_river2grid.txt
5.2 Run **SWAT_MODFLOW.exe** (rather than the original SWAT executable)
6. VIEWING RESULTS

The SWAT-MODFLOW simulation will produce several primary output files and, if selected in the *Simulation* tab, up to 6 additional output files:

**modflow.hed**

This file contains the calculated groundwater hydraulic head for each MODFLOW grid cell, for each specified time step of the simulation (the time steps at which values will be written are specified in the modflow.oc file). For each output time, there is a header line (time step, stress period), followed by the hydraulic head values written by row and column. No-data values (i.e. cells outside of the watershed boundary) are represented by “-999.0”.

**swatmf_out_MF_obs**

*Created only if flag is set in swatmf_link.txt*

This file contains the groundwater hydraulic head of the observation cells specified in “modflow.obs”, for each MODFLOW time step. For each time step, the head values for each observation cell are printed on a single line, in the same order as the cells listed in “modflow.obs”. These results can be used to create time series of hydraulic head for locations within the aquifer:
swatmf_out_SWAT_recharge
Created only if flag is set in swatmf_link.txt
This file contains the depth (mm) of deep percolation (= recharge to MODFLOW) calculated for each HRU, for each day of the simulation. Following the header line (“SWAT deep percolation (mm) (for each HRU)”), the deep percolation values for each HRU (beginning with HRU #1) are written for the first day, followed by a blank line, followed by the values for the next day, etc.

swatmf_out_MF_recharge
Created only if flag is set in swatmf_link.txt
This file contains the volumetric flow rate of recharge (m³/day) of recharge provided to each MODFLOW grid cell, for each day of the simulation. The values are written in a 2D format according to the number of rows and columns in the MODFLOW grid. These values can be displayed as raster datasets in GIS to display the recharge to the water table:
**swatmf_out_SWAT_channel**
*Created only if flag is set in swatmf_link.txt*
This file contains the channel depth (m) for each sub-basin channel, for each day of the simulation. For each day, the depths are written on a single line, with the depth for sub-basin #1 in the first column, depth for sub-basin #2 in the second column, etc. up to the last sub-basin.

**swatmf_out_MF_riverstage**
*Created only if flag is set in swatmf_link.txt*
This file contains the river stage (= channel depth) (m) for each MODFLOW river cell, for each day of the simulation. These values are obtained from the sub-basin channel depths computed by SWAT. Output from consecutive days is separated by a blank line.

**swatmf_out_SWAT_gwsw**
*Created only if flag is set in swatmf_link.txt*
This file contains the volumetric exchange rates (m$^3$/day) between the stream network and the aquifer for each SWAT sub-basin (numbered consecutively), for each day of the simulation. Positive values signify groundwater flow to the channel, whereas negative values signify stream seepage to the aquifer. Output from consecutive days is separated by a blank line.

**swatmf_out_MF_gwsw**
*Created only if flag is set in swatmf_link.txt*
This file contains the volumetric exchange rate (m$^3$/day) between the stream network and the aquifer for each MODFLOW River cell (numbered consecutively), for each day of the simulation. *Negative* values signify groundwater flow to the channel (MODFLOW treats the aquifer as the control volume, and water leaving the aquifer is denoted by a negative value), whereas positive values signify stream seepage to the aquifer (i.e. a source to the aquifer). Output from consecutive days is separated by a blank line.
7. Watershed Water Balance in SWAT-MODFLOW

For standard SWAT model simulations, the output.std file contains daily-averaged depths for the principal water balance variables in the watershed (e.g. rainfall, surface runoff, groundwater flow to streams, etc.). The output.std file for the SWAT-MODFLOW simulations has the same general format as the original SWAT model, but with several key additions that provide more information regarding groundwater and groundwater-surface water interactions. These additions are summarized as follows:

Variables in original SWAT simulations

- PREC: Rainfall in the watershed
- SURQ: Surface runoff to streams
- LATQ: Lateral flow to streams
- GWQ: Groundwater flow to streams (using original SWAT groundwater module)
- PERCO LATE: Deep percolation (recharge) to groundwater
- TILE Q: Tile drain flow to streams
- SW: Total soil water contained in the watershed
- WATER YIELD: Total water added to streams ( = SURQ + LATQ + GWQ + TILE Q)

New Variables (and changes to original variables) in SWAT-MODFLOW simulations

- GWQ: Groundwater flow to streams (as calculated by the River package in MODFLOW)
- SWGW: Seepage from streams to the aquifer (as calculated by the River package in MODFLOW)
- GW: Total groundwater contained in the watershed
- WATER YIELD: Total water added to streams ( = SURQ + LATQ + GWQ – SWGW + TILE Q) (notice that this takes into account the water that leaves the stream and seeps into the aquifer)
8. WATER QUALITY USING SWAT-MODFLOW-RT3D

SWAT-MODFLOW can also be used in conjunction with the RT3D (Reactive Transport in 3 Dimensions) model to simulate the reactive transport of solutes through the aquifer system and the solute mass exchange between the aquifer and the stream network. RT3D is called as a subroutine within the MODFLOW code during each groundwater flow time step. RT3D uses the same finite difference grid as MODFLOW.

In the current version of the code, Nitrate (NO₃) is included as a groundwater solute. Nitrate mass in deep percolation water as simulated for each SWAT HRU is passed to RT3D grid cells using the same HRU-Cell mapping procedures as described in the previous sections of this tutorial. MODFLOW provides the cell-by-cell flow rates for each grid cell, and then RT3D calculates the cell-by-cell NO₃ concentration in the aquifer and the NO₃ mass loading from the aquifer to the stream network. Using the River Cell – Subbasin linking procedure as described in Section 2.1.4, the NO₃ mass loading from the aquifer to the stream is provided to the correct subbasin, which then can be routed through the watershed streams using the SWAT N-routing algorithms.

If solute transport with RT3D is desired, the “rt_active” flag in the `swatmf_link.txt` input file must be set to “1”. There are also several RT3D input files required. These files are not described in this tutorial. If the user desires to use RT3D, please contact Dr. Ryan Bailey at Colorado State University for help in setting up a SWAT-MODFLOW-RT3D model.

9. SWATMOD-PREP: GRAPHICAL USER INTERFACE FOR CREATING SWAT-MODFLOW SIMULATIONS

SWATMOD-Prep is a graphical user interface that facilitates the linkage of SWAT and MODFLOW simulations to run a coupled SWAT-MODFLOW simulation. The executable for installing SWATMOD-Prep on a PC and an accompanying tutorial using the Little River Watershed dataset are provided on the SWAT-MODFLOW website (http://swat.tamu.edu/software/swat-modflow/).