
# SWAT-MODFLOW Tutorial

## Version 3

**Documentation for preparing and running SWAT-MODFLOW simulations**

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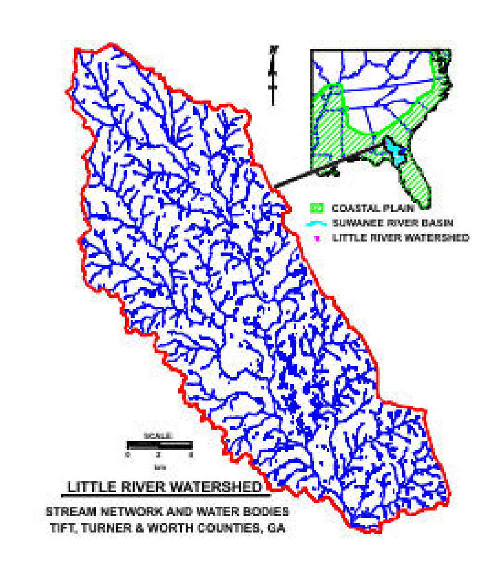
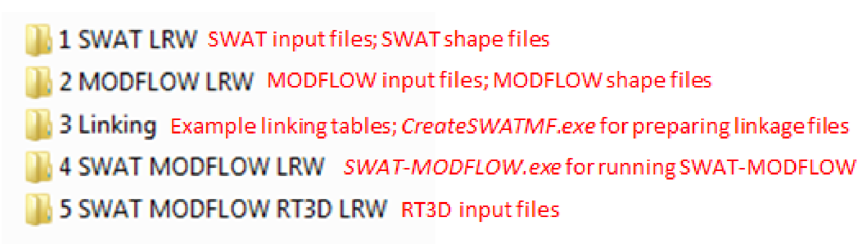
# OVERVIEW OF TUTORIAL

This tutorial provides the basic procedure for preparing a SWAT-MODFLOW model for coupled surface-subsurface hydrologic modeling, based on the modeling code of Bailey et al. (2016). The theory and procedure for coupling the two models are discussed, followed by a step-by-step process for linking, running a simulation, and viewing results. The procedure for running the model with nitrogen and phosphorus groundwater transport using the RT3D code also is presented. *This tutorial assumes that SWAT and MODFLOW models have already been constructed for the study area.*

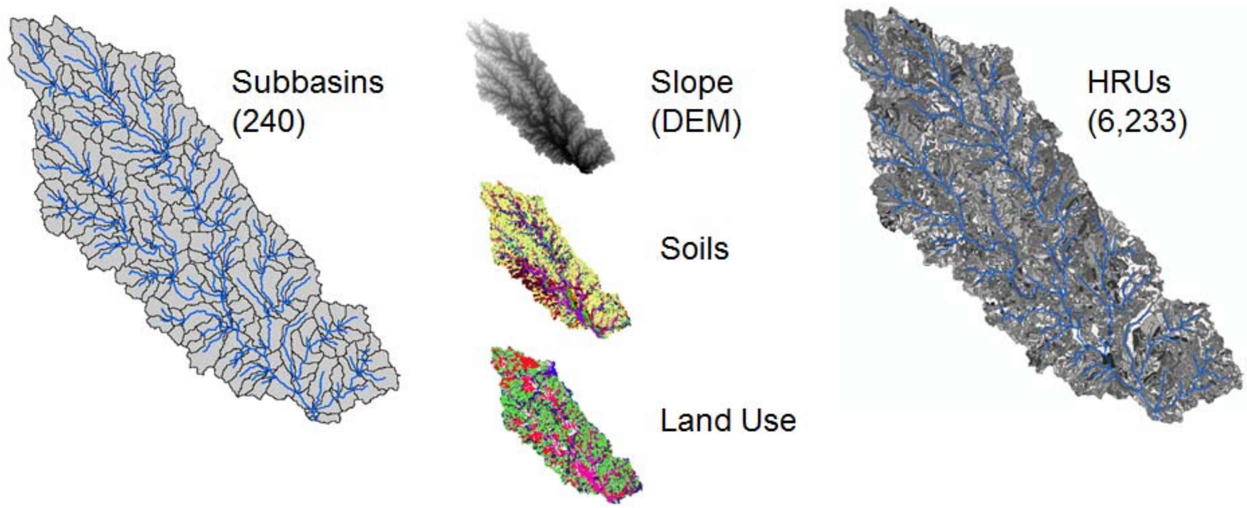
The steps for linking, preparing all necessary input files, viewing results, and including RT3D for nitrogen and phosphorus transport are provided using existing SWAT and MODFLOW models for the Little River Watershed (LRW), a 330 km$^2$ catchment in southern Georgia, USA:



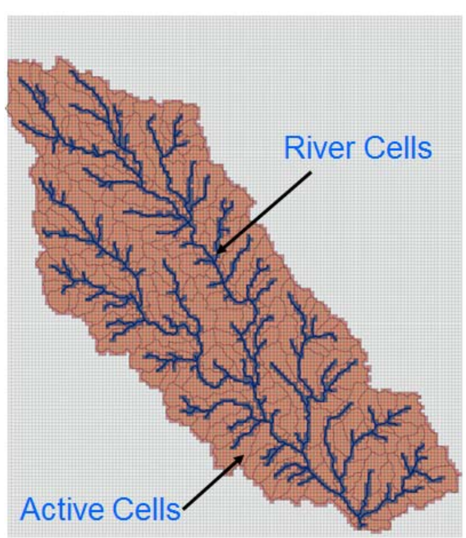

All required input files and program executables are contained within the **Files** folder, with 5 sub-folders numbered according to their order of use in the tutorial:



The model has a simulation period of 15 years, from 1988 to 2002. The SWAT model consists of 240 subbasins and 6,233 HRUs. The SWAT input files are contained in **Files\1 SWAT LRW\SWAT Model\TxtInOut.** The shape files for the SWAT model are contained in **Files\1 SWAT LRW\SWAT Model shapefiles**, and will be used in this tutorial to link with the MODFLOW grid cells.




The MODFLOW model has grid cells with dimensions of 200 m x 200 m, resulting in 141 rows and 136 columns in the finite difference grid for a total of 19,176 cells. The model has one layer and 1,633 River Cells (i.e. cells for which the aquifer can exchange water with the stream network). The MODFLOW input files are contained in **Files\2 MODFLOW LRW\MODFLOW model**, along with the MODFLOW executable MODFLOW-NWT.exe (Niswonger et al., 2011). The executable can be run (double-click executable, type in name file modflow.mfn) with these files for a steady-state solution. The run mode will be changed to transient (i.e. time-dependent) when linked with SWAT, as shown later in this tutorial. The shape files for the MODFLOW grid are contained in **Files\2 MODFLOW LRW\MODFLOW model shapefiles**, and will be used in this tutorial to link with SWAT HRUs and subbasins.

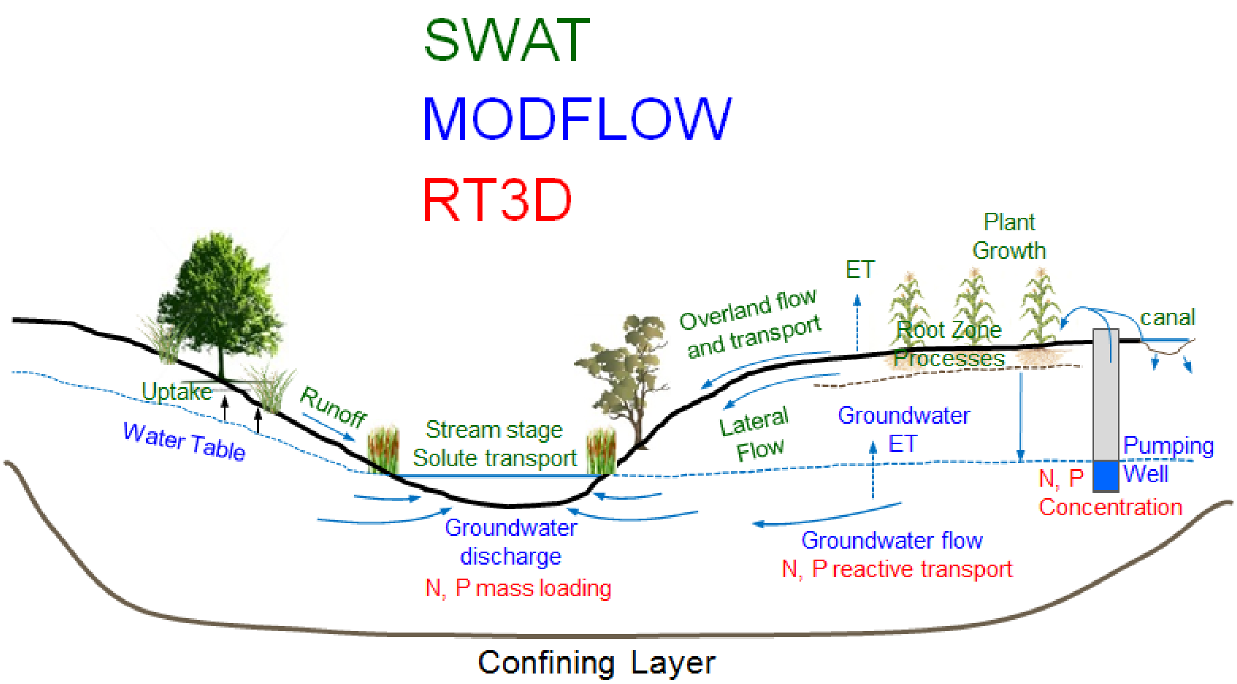


# Tutorial Contents

# 1. Overview of SWAT-MODFLOW

SWAT-MODFLOW is a 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 watersheds. Transport of nitrogen (N) and phosphorus (P) in this system is simulated by including the RT3D (Reactive Transport in 3 Dimensions) (Clement, 1997; Clement et al., 1998) model into the MODFLOW groundwater routines.

The processes simulated by each model are shown in the following figure. Processes simulated by SWAT are shown with green text, those simulated by MODFLOW in blue text, and those simulated by RT3D 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 N and P transport in the aquifer and nutrient mass exchange between groundwater and surface water. Transport of groundwater and associate mass of N and P from the bottom of the soil profile to the water table is simulated using a groundwater delay function.



## 2. OVERVIEW OF THE LINKING PROCEDURE

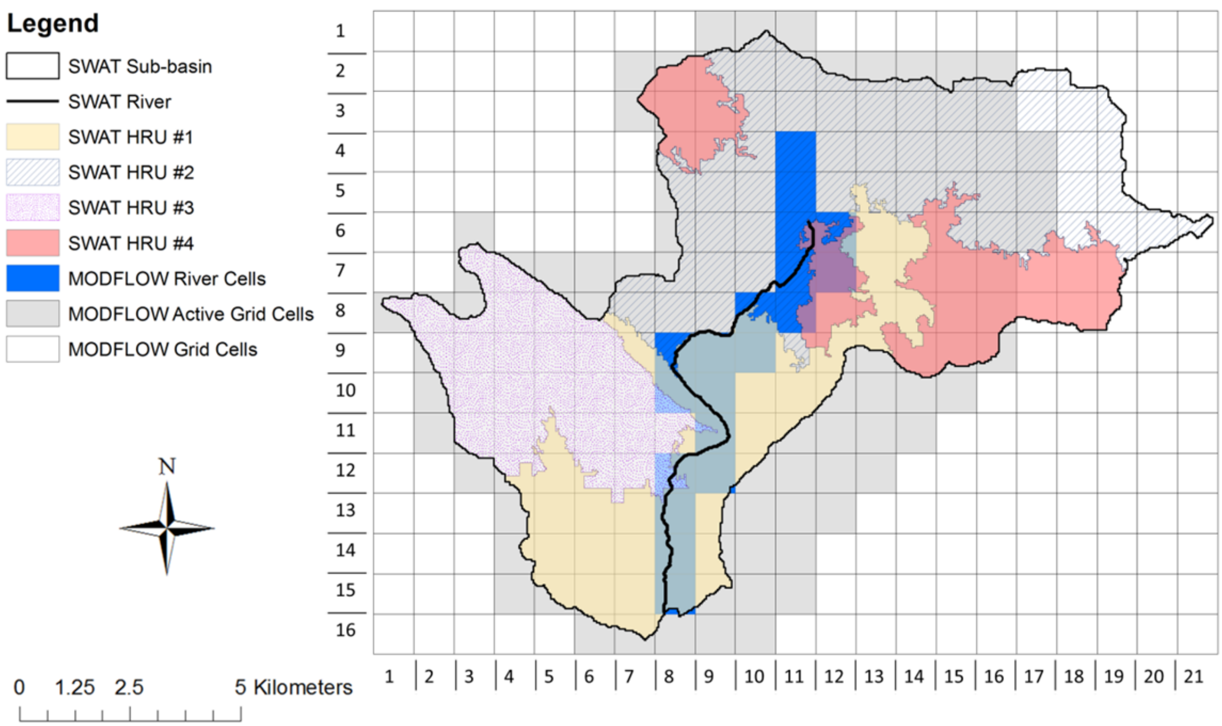
Running a coupled SWAT-MODFLOW model requires that values of state variables be passed ("mapped") from the SWAT model to the MODFLOW model and from the MODFLOW model back to the SWAT model. The following state variables are passed between the two models:

- **Recharge to the water table** (SWAT HRUs → MODFLOW grid cells)
- **Difference between potential ET and actual ET*** (SWAT HRUs → MODFLOW grid cells)
- **Subbasin channel stage** (SWAT subbasin channels → MODFLOW river cells)
- **Groundwater-Stream exchange rates** (MODFLOW River Cells → SWAT subbasin channels)

* This difference can be transpired from groundwater if the water table is above a prescribed extinction depth, using MODFLOW's Evapotranspiration (EVT) package.

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 recharge rates and remaining ET rates from SWAT HRUs to MODFLOW grid cells. 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.

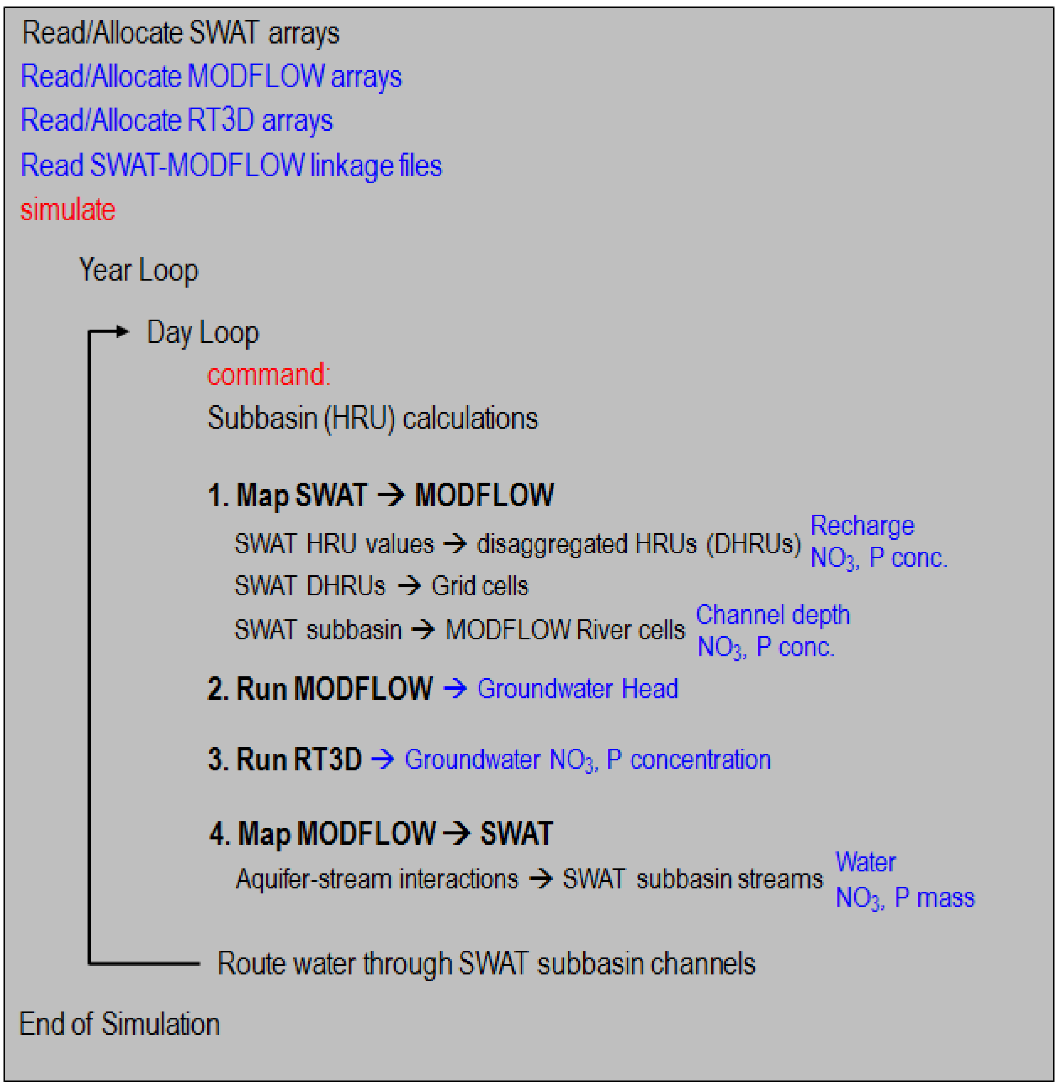
When SWAT-MODFLOW is active, the original SWAT groundwater module is turned off. The delay of soil water percolation reaching the water table, however, is still active and is used to mimic groundwater transport in the vadose zone. As with the original groundwater module, a unique value of groundwater delay can be assigned to each HRU, which is used to compute HRU-based recharge that is then mapped the MODFLOW grid cells.


Legend
SWAT Sub-basin
SWAT River
SWAT HRU #1
SWAT HRU #2
SWAT HRU #3
SWAT HRU #4
MODFLOW River Cells
MODFLOW Active Grid Cells
MODFLOW Grid Cells
N
0 1.25 2.5 5 Kilometers
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21

## 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. If RT3D is set to active for simulating $NO_3$ and P transport in the aquifer, then RT3D is called after MODFLOW. 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 RT3D, and then mapping variables back to SWAT. Routing of surface return flow, groundwater return flow, and N and P mass through the watershed stream network then can be performed for that day.

**SWAT-MODFLOW Code Structure**



# 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)

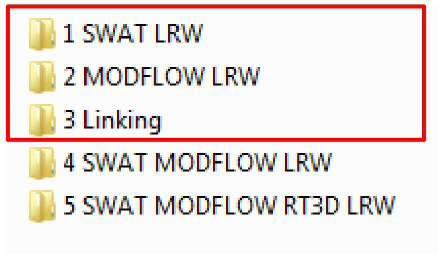
The linkage information is stored in memory during the simulation and used when variables are passed between the two models. The process of creating each of the 4 text files is as follows:

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 folders **1 SWAT LRW**, **2 MODFLOW LRW**, and **3 Linking**:



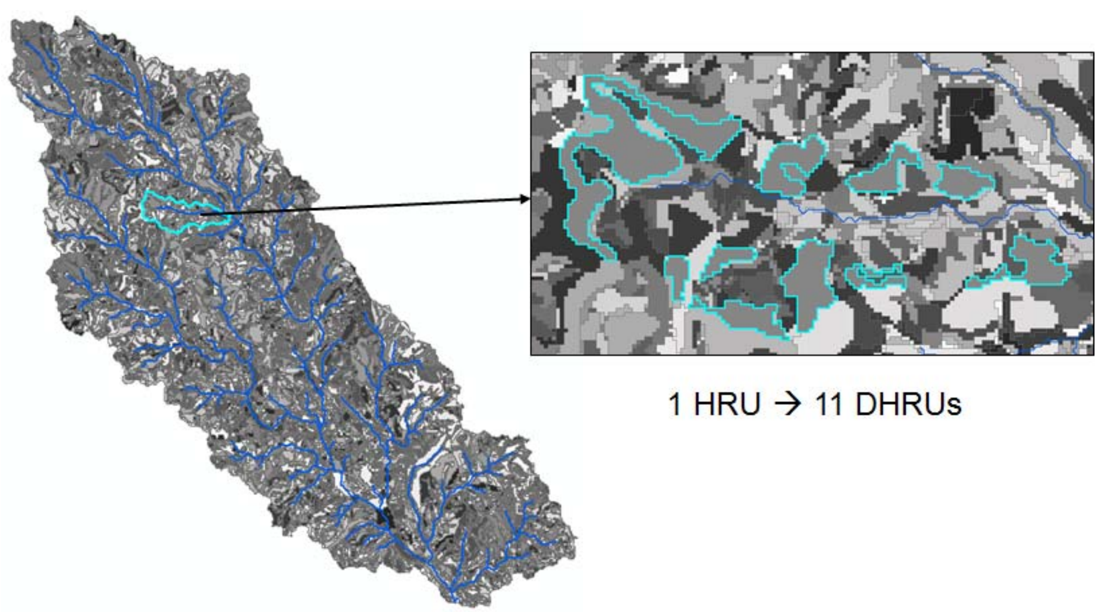

Files in the **3 Linking** folder are provided for convenience. The process of creating these files is described in this section.

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)

This section describes the process for linking HRUs with Disaggregated HRUs (DHRUs). Disaggregation splits apart an HRU into individual polygons that have a specific geographic location. For example, the following map shows 11 DHRUs that are split apart from 1 single HRU:



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

<u>At the top of the file</u>:

*Number of DHRUs*
*Number of HRUs*

<u>Then, the following columns</u>:

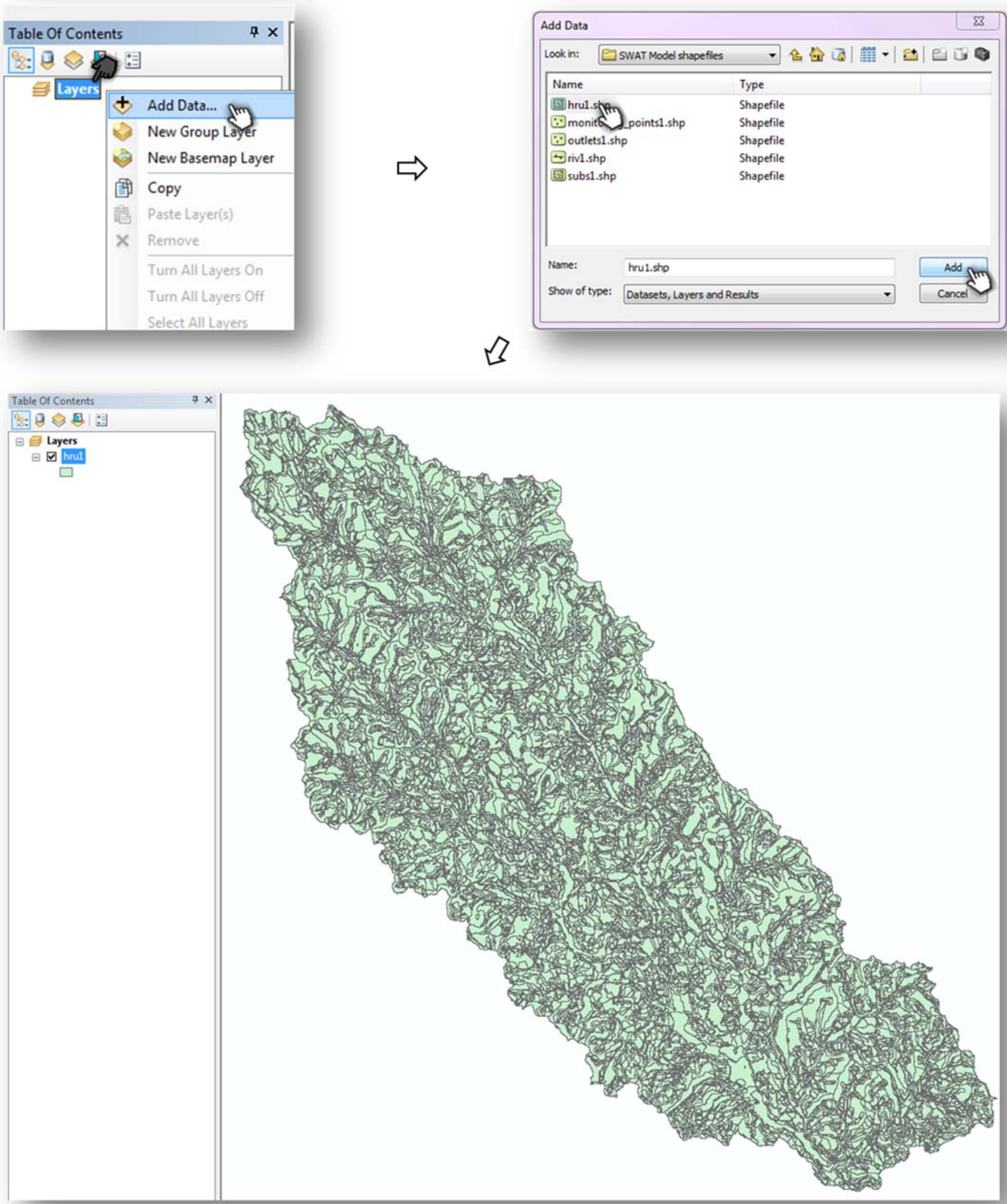
*dhru_id*: ID of DHRU (sequential numbering)
*dhru_area*: Spatial Area ($m^2$) of the DHRU
*hru_id*: ID of the HRU from which the DHRU originates
*subbasin*: ID of the Subbasin
*hru_area*: Spatial area ($m^2$) of the original HRU

<u>For example</u>:

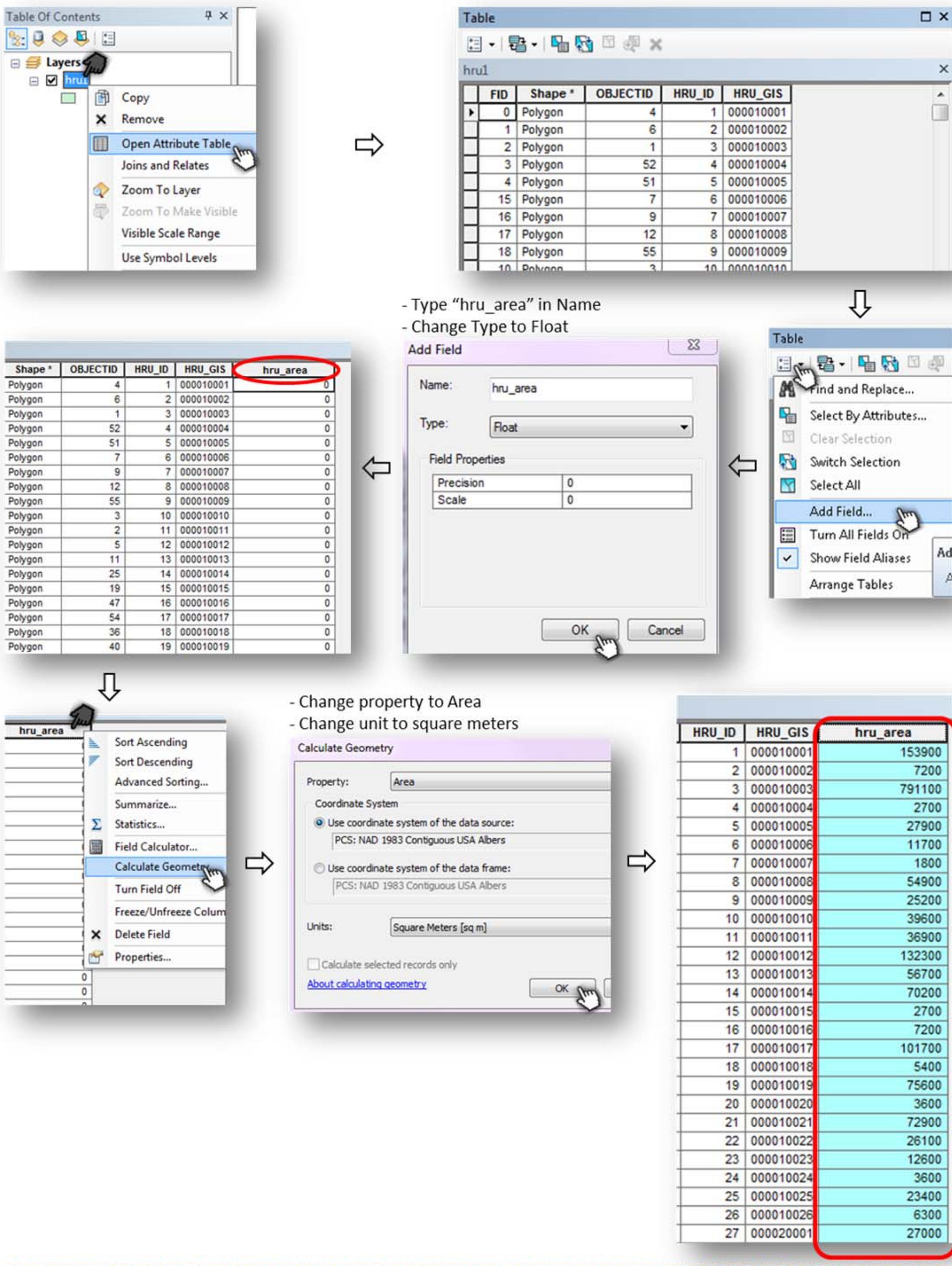
```
27396
6233
dhru_id dhru_area  hru_id   subbasin hru_area
1       9000     1         1       153900
2       900      1         1       153900
3       900      1         1       153900
4       900      1         1       153900
5       45900    1         1       153900
6       89100    1         1       153900
7       7200     1         1       153900
8       900      2         1       7200
9       900      2         1       7200
10      900      2         1       7200
11      900      2         1       7200
12      1800     2         1       7200
13      1800     2         1       7200
14      54000    3         1       791100
15      423000   3         1       791100
16      900      3         1       791100
17      900      3         1       791100
18      63900    3         1       791100
19      5400     3         1       791100
20      1800     3         1       791100
21      900      3         1       791100
22      900      3         1       791100
23      900      3         1       791100
24      900      3         1       791100
25      225900   3         1       791100
26      1800     3         1       791100
27      9900     3         1       791100
28      2700     4         1       2700
```

## 1. Begin with HRU shapefile (no thresholds)

① Import the “hru1” shapefile (1 SWAT LRW folder) into ArcMap

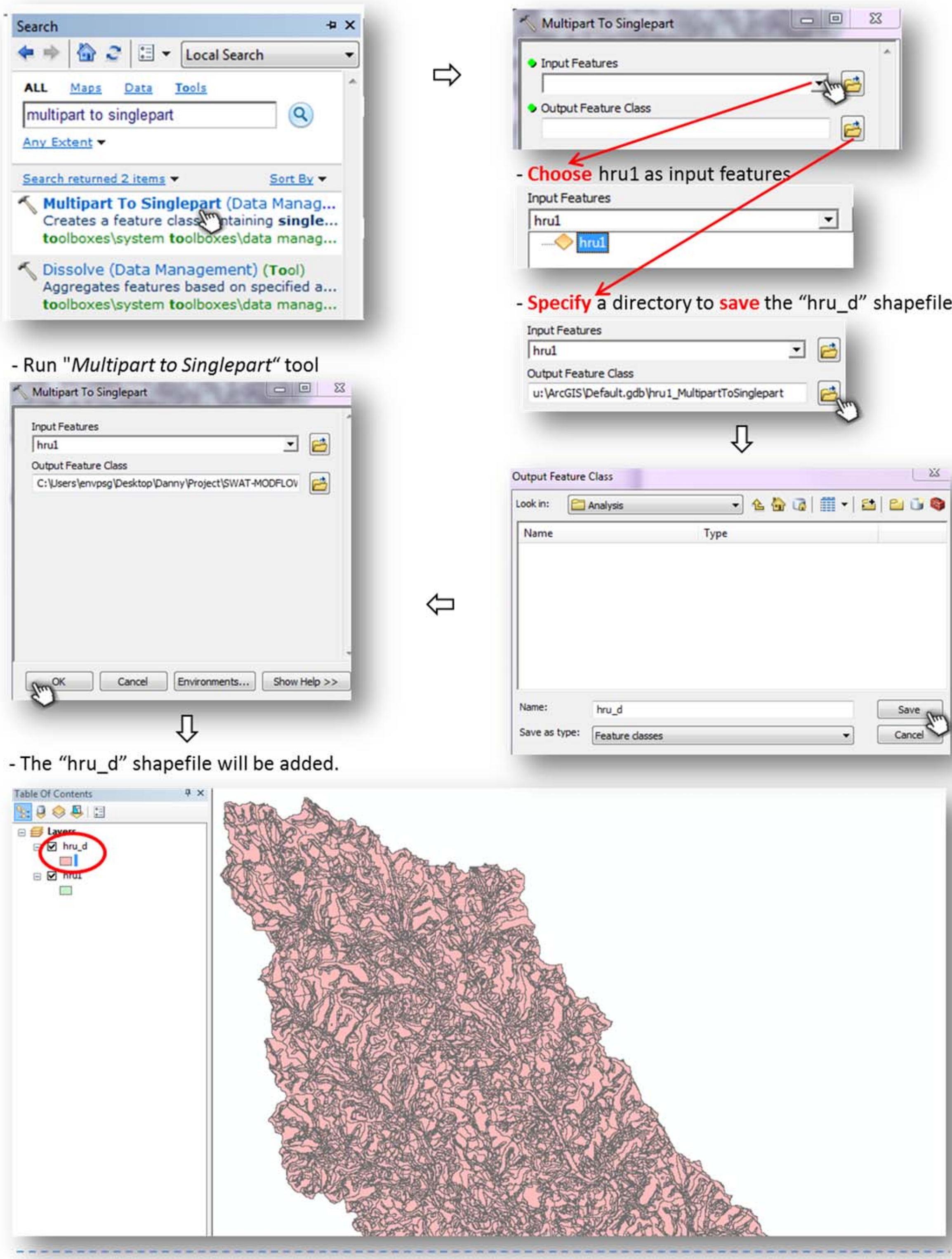


② Add the spatial area ($m^2$) of the HRUs in the "hru_area" field



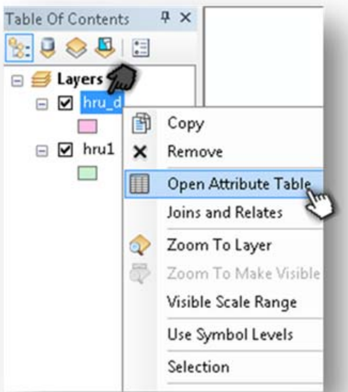
**2. Apply the GIS operation "*Multipart to Singlepart*" to create the DHRU shape file**

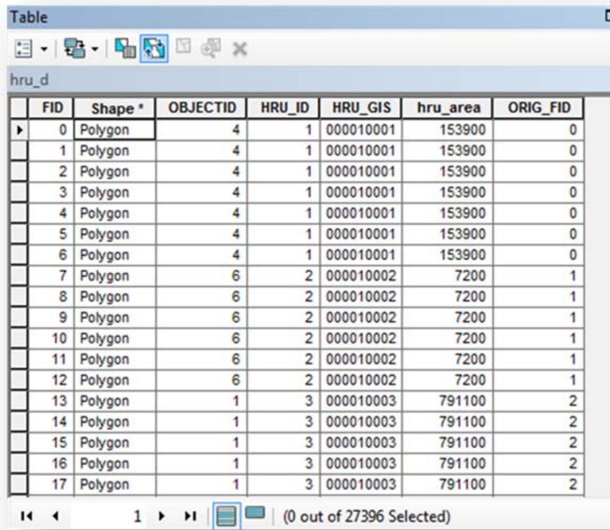
① Open “Multipart to Singlepart” tool



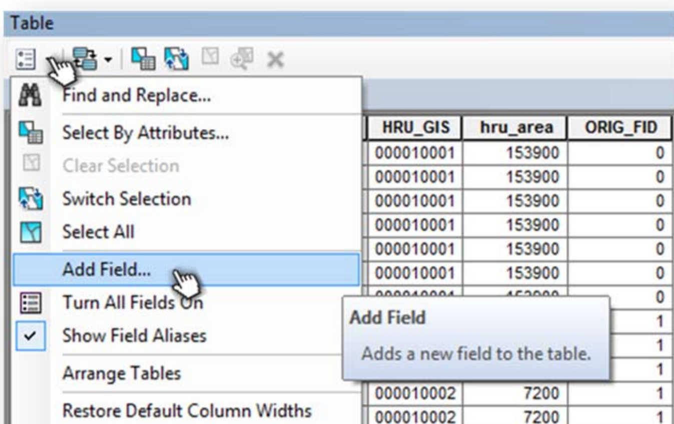
## 3. Get Area, unique ID, and subbasin for each DHRU

① Open the attribute table of the "hru_d" shapefile

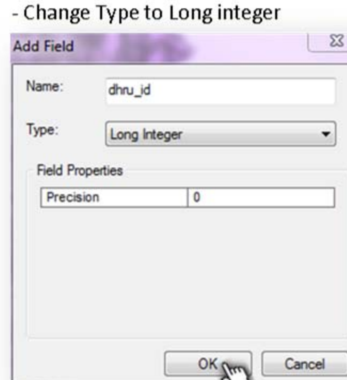


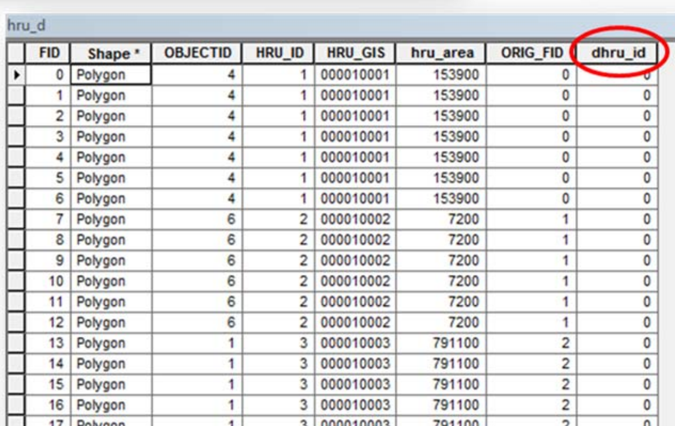




② Create "dhru_id" field with long integer type

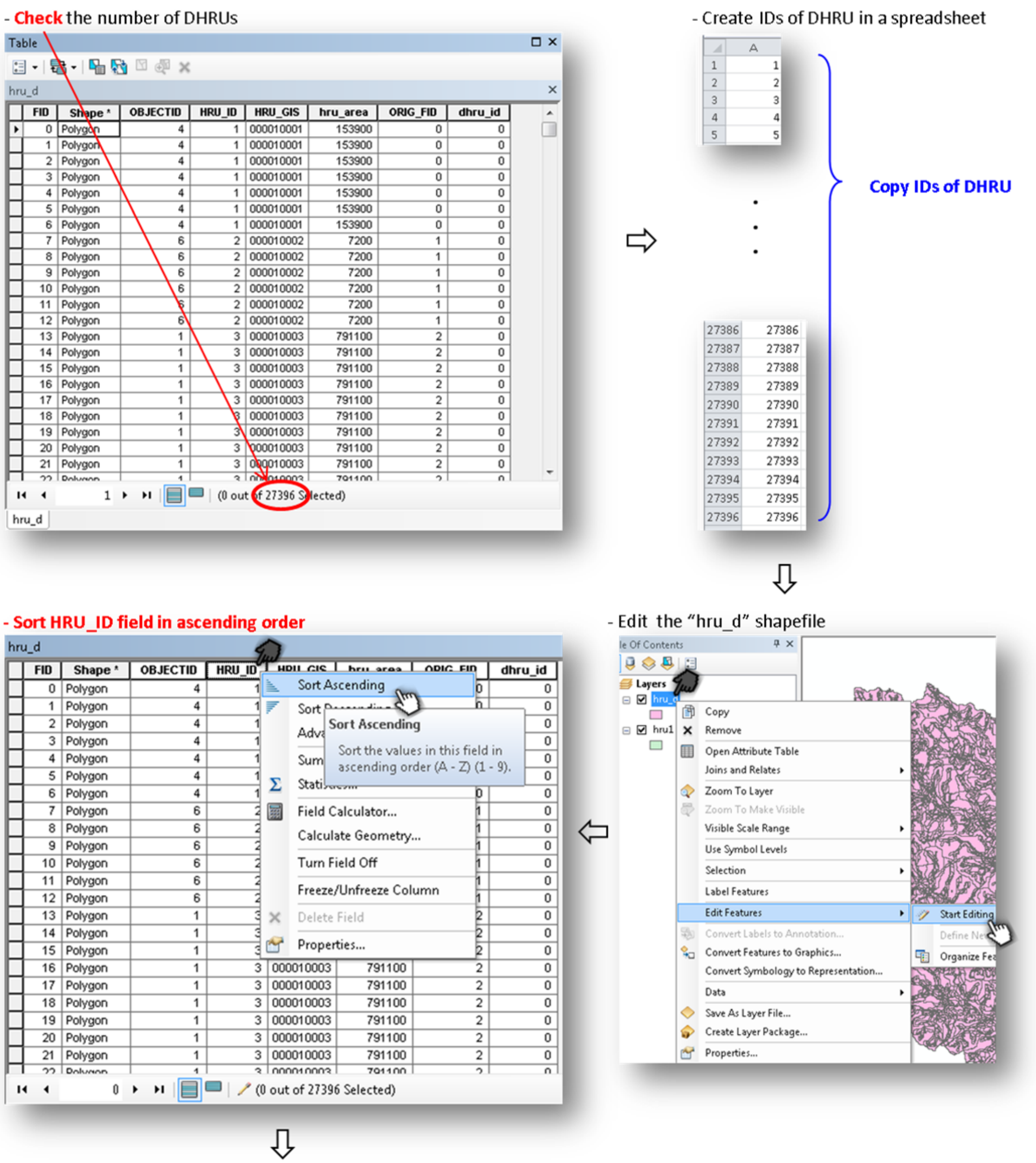



- Type dhru_id in Name
- Change Type to Long integer



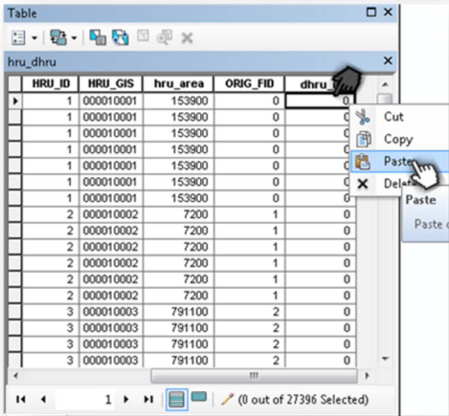



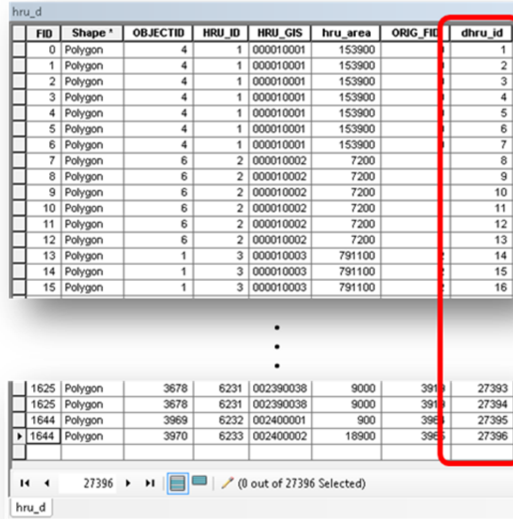
③ Create IDs for the DHRUs in a spreadsheet of Excel. *It is important that the HRUs are sorted by ID before providing IDs to each DHRU. This will be described in this step.*



- 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

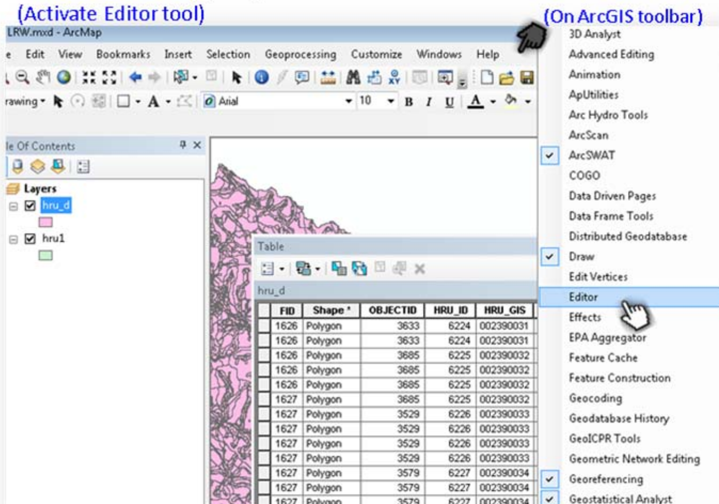


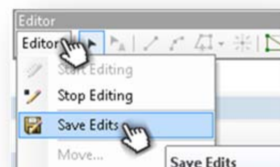



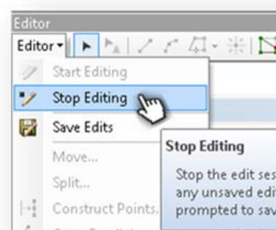

- Save the edited hru_d shapefile

(Activate Editor tool)

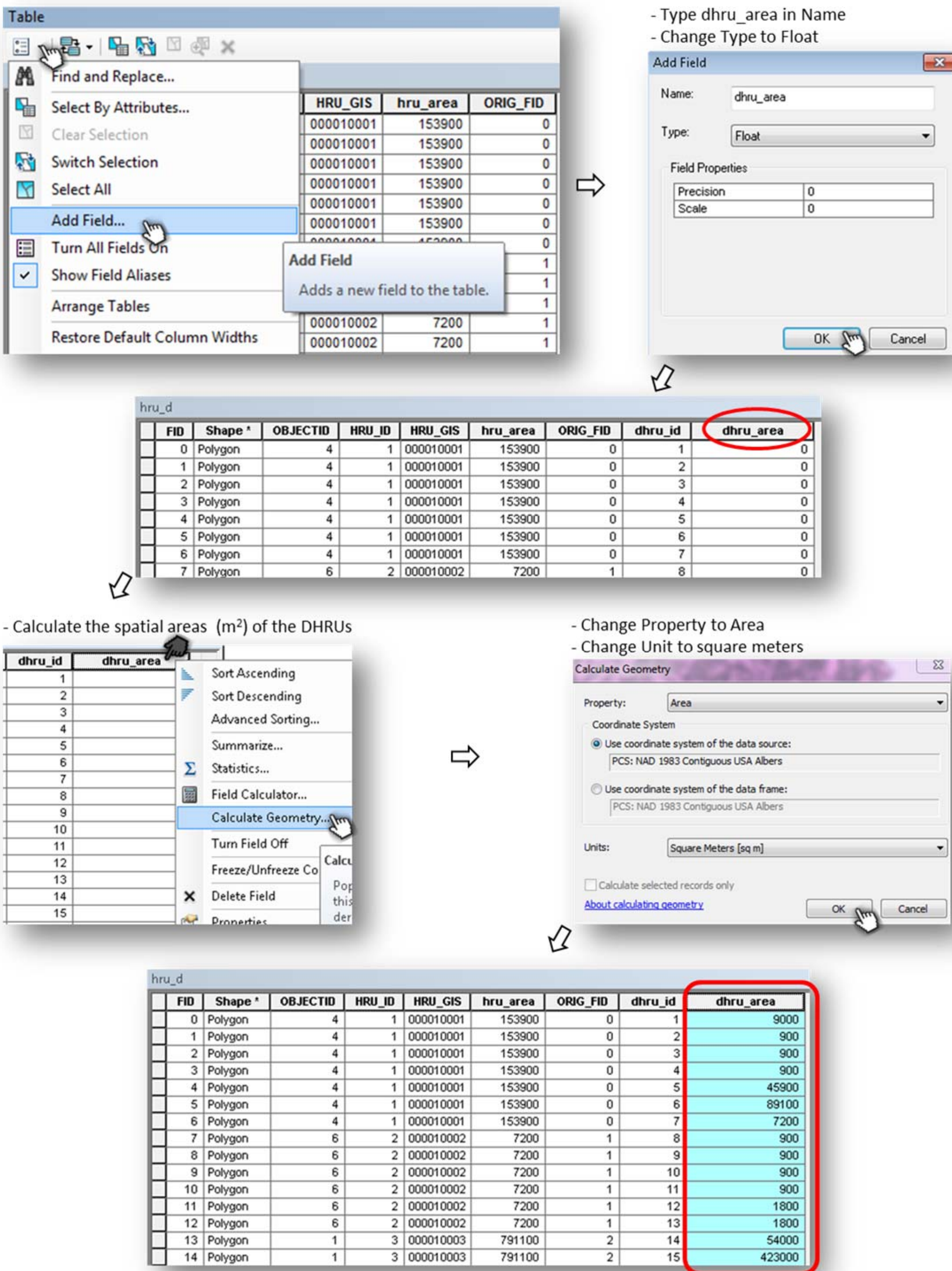
(On ArcGIS toolbar)



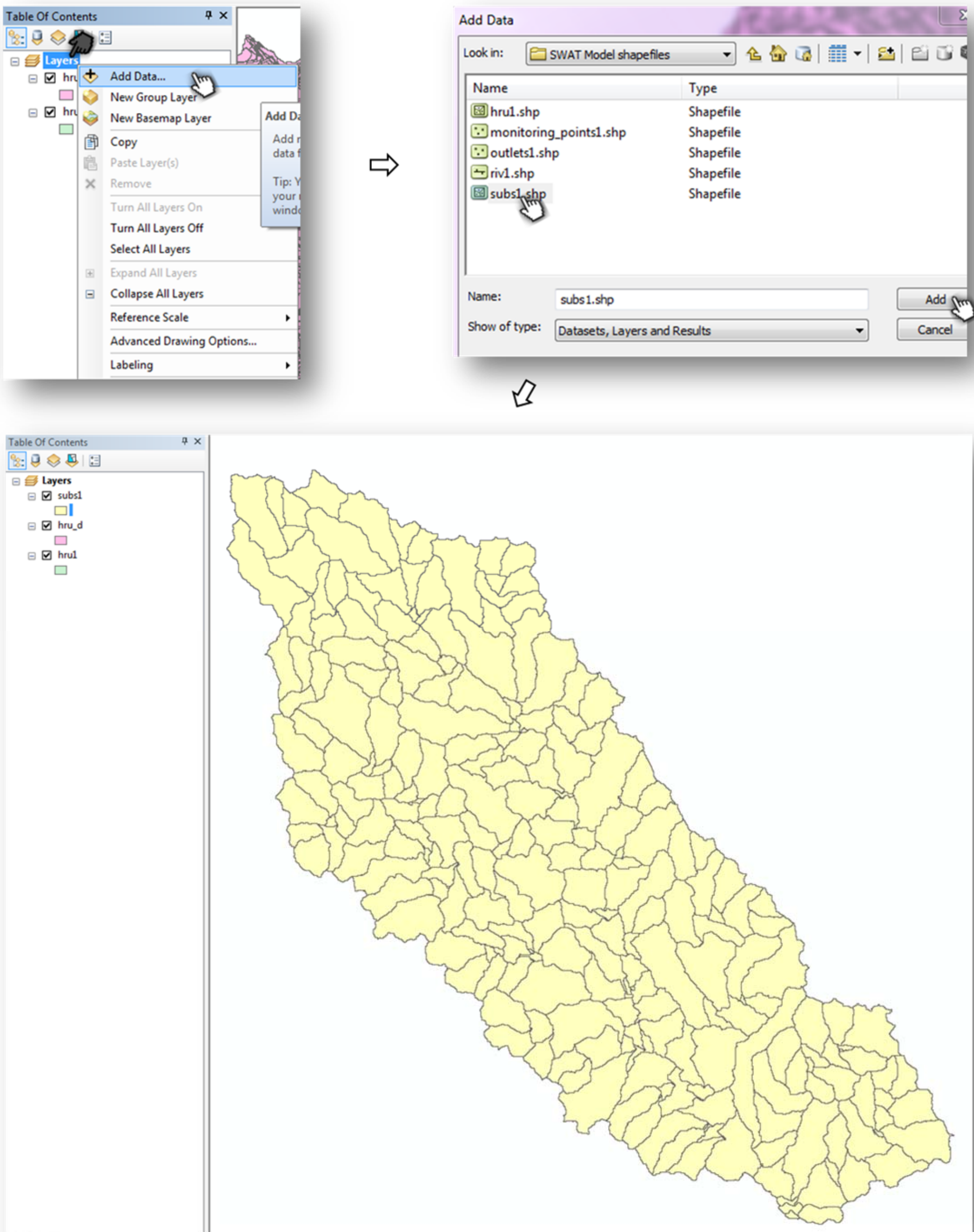



④ Create “dhru_area” field with float type

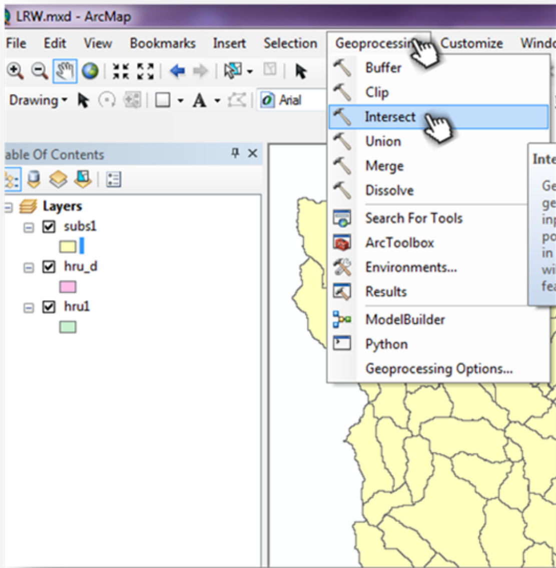


⑤ Intersect the “hru_d” with the “sub1” shapefile

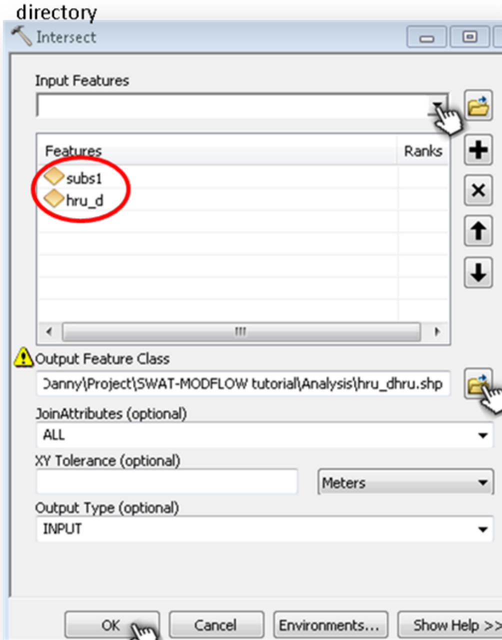
- Add the “sub1” shapefile to layer

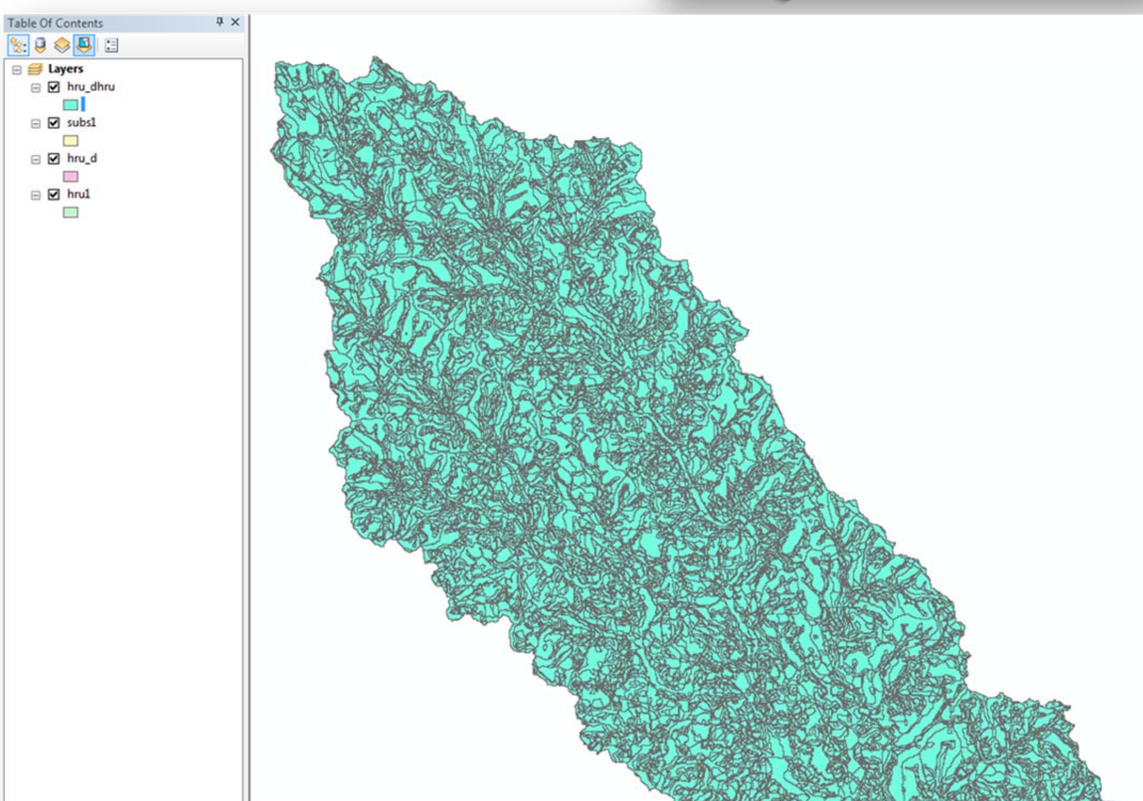


- Run Intersect tool

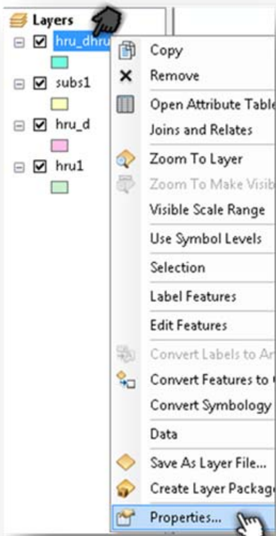



- Add the “sub1” and “hru_d” shapefiles in Input Features
- Specify the output feature class name (hru_dhru) and directory

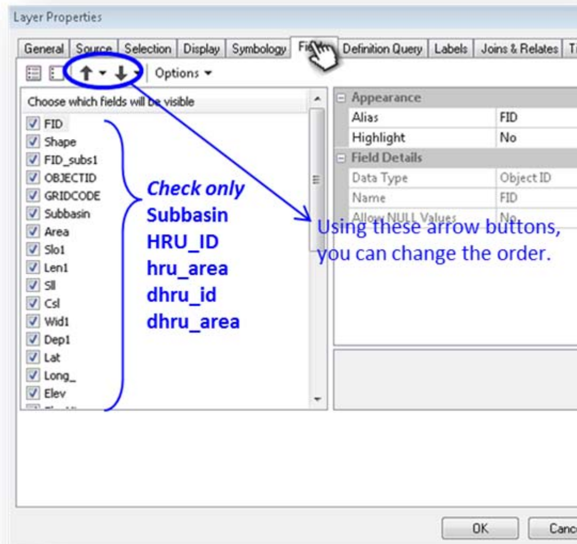


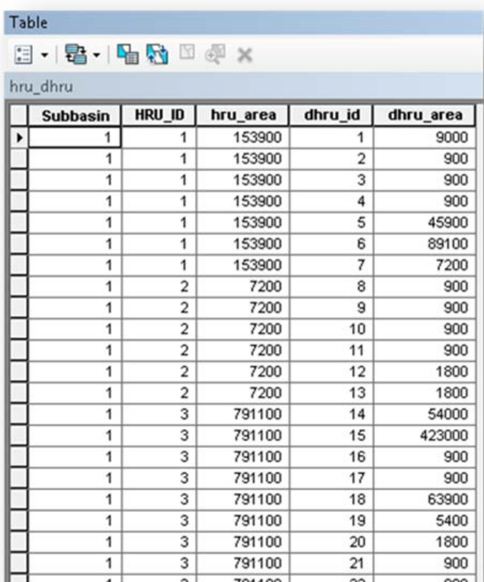
⑥ Select only the necessary fields (You can either turn off or delete an unnecessary field)




⇨

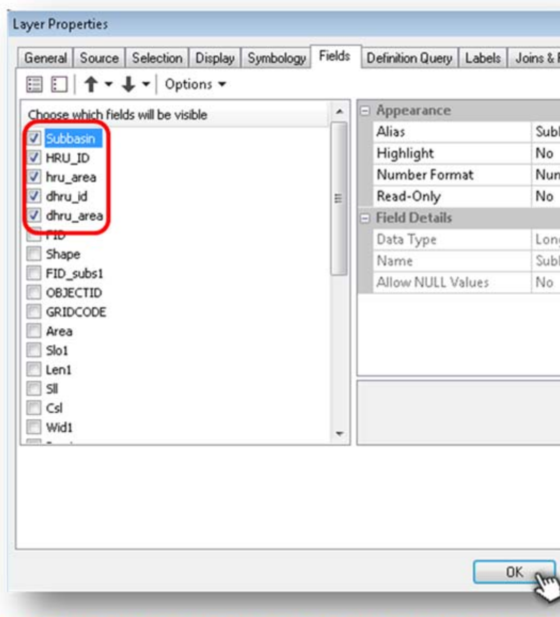



⇩



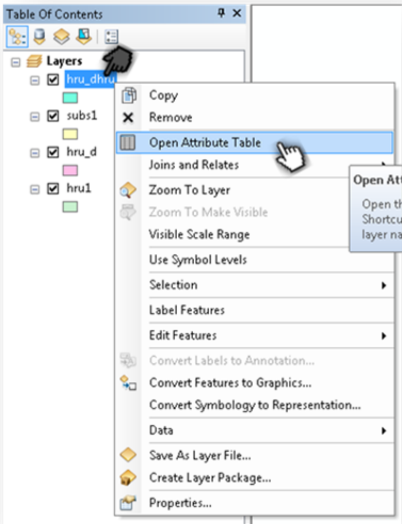

| Subbasin | HRU_ID | hru_area | dhru_id | dhru_area |
|---|---|---|---|---|
| 1 | 1 | 153900 | 1 | 9000 |
| 1 | 1 | 153900 | 2 | 900 |
| 1 | 1 | 153900 | 3 | 900 |
| 1 | 1 | 153900 | 4 | 900 |
| 1 | 1 | 153900 | 5 | 45900 |
| 1 | 1 | 153900 | 6 | 89100 |
| 1 | 1 | 153900 | 7 | 7200 |
| 1 | 2 | 7200 | 8 | 900 |
| 1 | 2 | 7200 | 9 | 900 |
| 1 | 2 | 7200 | 10 | 900 |
| 1 | 2 | 7200 | 11 | 900 |
| 1 | 2 | 7200 | 12 | 1800 |
| 1 | 2 | 7200 | 13 | 1800 |
| 1 | 3 | 791100 | 14 | 54000 |
| 1 | 3 | 791100 | 15 | 423000 |
| 1 | 3 | 791100 | 16 | 900 |
| 1 | 3 | 791100 | 17 | 900 |
| 1 | 3 | 791100 | 18 | 63900 |
| 1 | 3 | 791100 | 19 | 5400 |
| 1 | 3 | 791100 | 20 | 1800 |
| 1 | 3 | 791100 | 21 | 900 |
| 1 | 3 | 791100 | 22 | 900 |

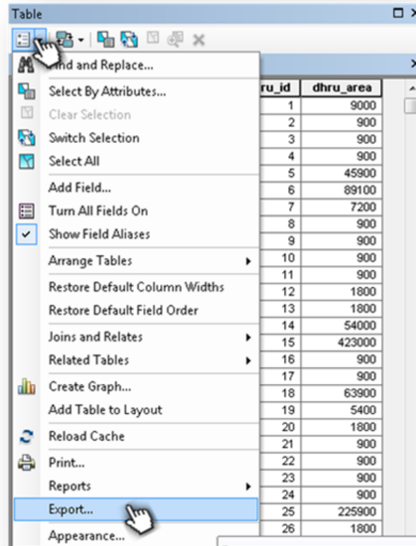
⇦



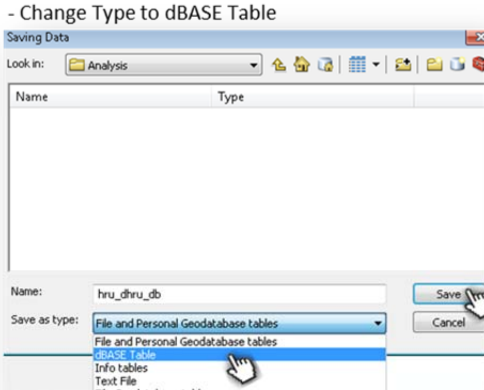
⑦ Provide text file: **hru_dhru** (This file is sorted by the HRU and DHRU IDs)

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

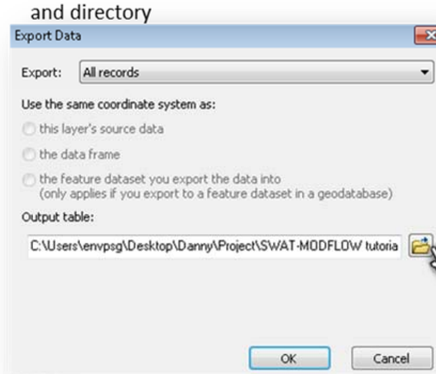



- Change Type to dBASE Table



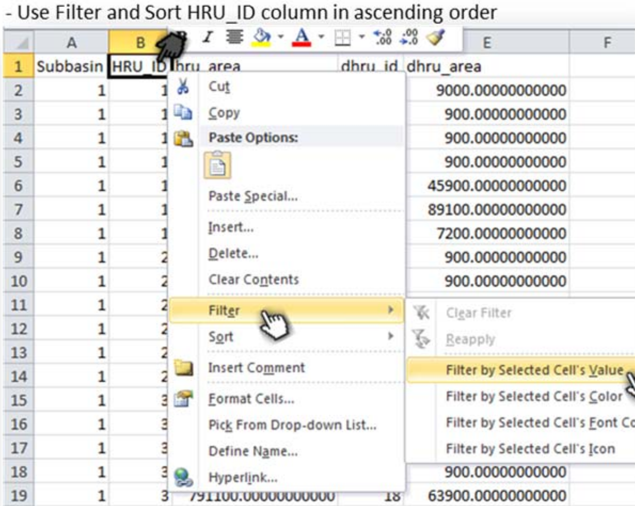

- Specify the output table name (hru_dhru_db) and directory

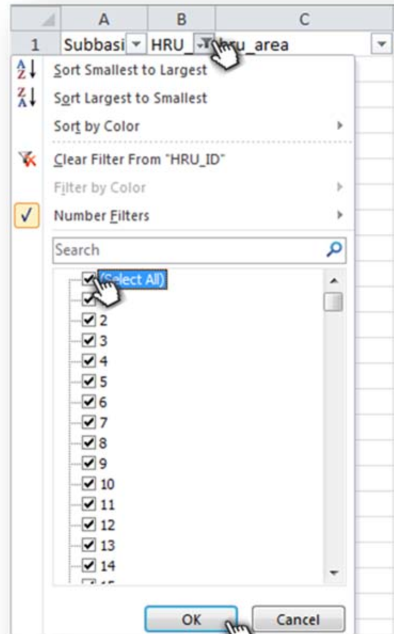


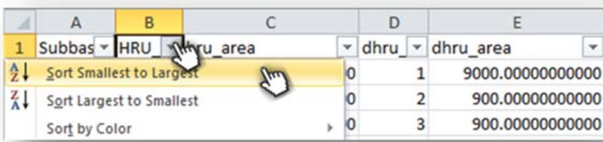

- Open the "hru_dhru_db" file with Excel

| | A | B | C | D | E |
|---|---|---|---|---|---|
| 1 | Subbasin | HRU_ID | hru_area | dhru_id | dhru_area |
| 2 | 1 | 1 | 153900.00000000000 | 1 | 9000.00000000000 |
| 3 | 1 | 1 | 153900.00000000000 | 2 | 900.00000000000 |
| 4 | 1 | 1 | 153900.00000000000 | 3 | 900.00000000000 |
| 5 | 1 | 1 | 153900.00000000000 | 4 | 900.00000000000 |
| 6 | 1 | 1 | 153900.00000000000 | 5 | 45900.00000000000 |
| 7 | 1 | 1 | 153900.00000000000 | 6 | 89100.00000000000 |
| 8 | 1 | 1 | 153900.00000000000 | 7 | 7200.00000000000 |
| 9 | 1 | 2 | 7200.00000000000 | 8 | 900.00000000000 |
| 10 | 1 | 2 | 7200.00000000000 | 9 | 900.00000000000 |
| 11 | 1 | 2 | 7200.00000000000 | 10 | 900.00000000000 |

- Use Filter and Sort HRU_ID column in ascending order



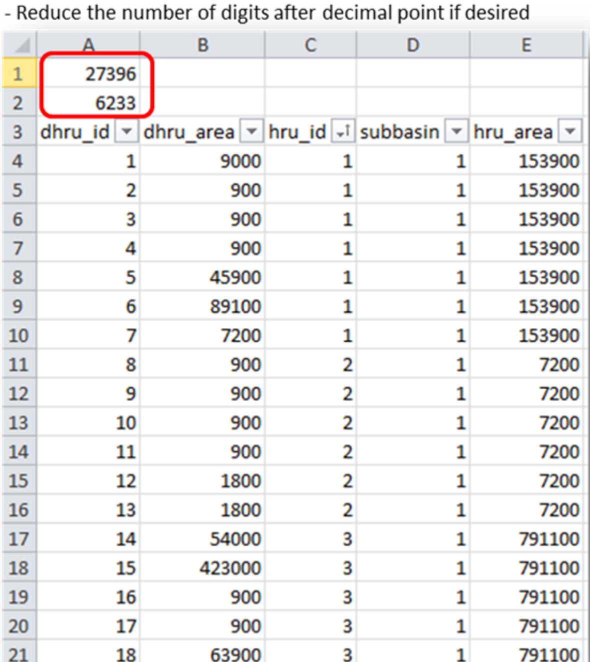




- Change the order of the columns and correct the column names

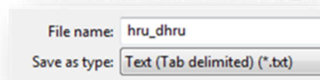
- Insert two rows at the top of the spreadsheet and write the numbers of DHRUs in 1st and HRUs in 2nd row

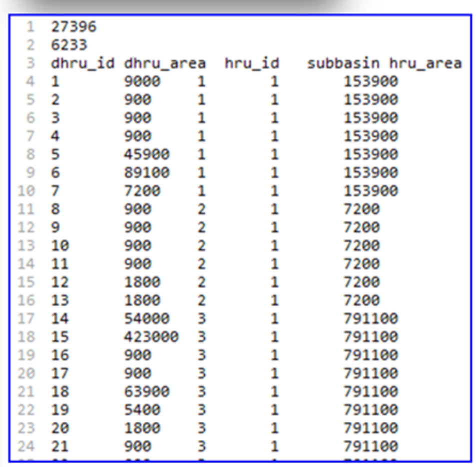
- Reduce the number of digits after decimal point if desired



| | A | B | C | D | E |
|---|---|---|---|---|---|
| 1 | 27396 | | | | |
| 2 | 6233 | | | | |
| 3 | dhru_id | dhru_area | hru_id | subbasin | hru_area |
| 4 | 1 | 9000 | 1 | 1 | 153900 |
| 5 | 2 | 900 | 1 | 1 | 153900 |
| 6 | 3 | 900 | 1 | 1 | 153900 |
| 7 | 4 | 900 | 1 | 1 | 153900 |
| 8 | 5 | 45900 | 1 | 1 | 153900 |
| 9 | 6 | 89100 | 1 | 1 | 153900 |
| 10 | 7 | 7200 | 1 | 1 | 153900 |
| 11 | 8 | 900 | 2 | 1 | 7200 |
| 12 | 9 | 900 | 2 | 1 | 7200 |
| 13 | 10 | 900 | 2 | 1 | 7200 |
| 14 | 11 | 900 | 2 | 1 | 7200 |
| 15 | 12 | 1800 | 2 | 1 | 7200 |
| 16 | 13 | 1800 | 2 | 1 | 7200 |
| 17 | 14 | 54000 | 3 | 1 | 791100 |
| 18 | 15 | 423000 | 3 | 1 | 791100 |
| 19 | 16 | 900 | 3 | 1 | 791100 |
| 20 | 17 | 900 | 3 | 1 | 791100 |
| 21 | 18 | 63900 | 3 | 1 | 791100 |

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

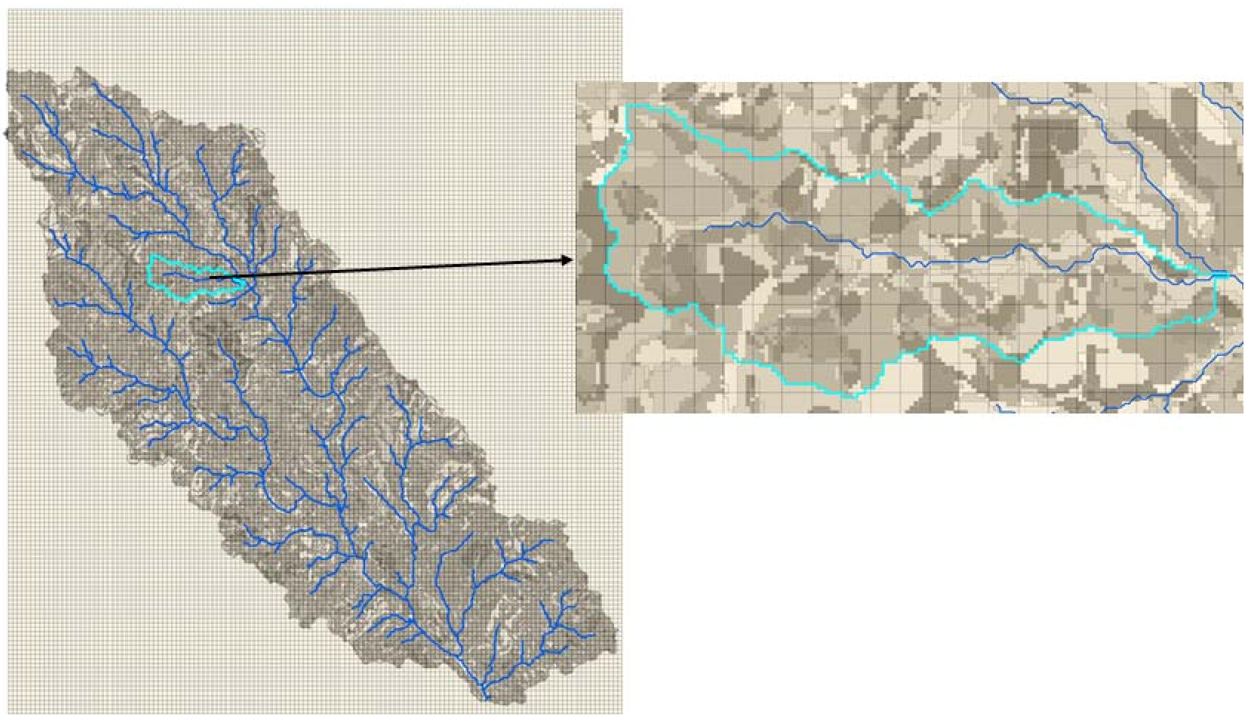


```
27396
6233
dhru_id dhru_area  hru_id   subbasin hru_area
1       9000       1        1        153900
2       900        1        1        153900
3       900        1        1        153900
4       900        1        1        153900
5       45900      1        1        153900
6       89100      1        1        153900
7       7200       1        1        153900
8       900        2        1        7200
9       900        2        1        7200
10      900        2        1        7200
11      900        2        1        7200
12      1800       2        1        7200
13      1800       2        1        7200
14      54000      3        1        791100
15      423000     3        1        791100
16      900        3        1        791100
17      900        3        1        791100
18      63900      3        1        791100
19      5400       3        1        791100
20      1800       3        1        791100
21      900        3        1        791100
```

### 4.1.2 Linkage between DHRUs and MODFLOW Grid Cells

This section describes the process for linking DHRUs with MODLFOW Grid cells, so that SWAT data can be transferred to the MODFLOW grid. For example, the following map shows the intersection between DHRU polygons and the MODFLOW grid cells:



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

<u>At the top of the file</u>:

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

<u>Then, the following columns</u> (sorted by *grid_id*, then by *dhru_id*):

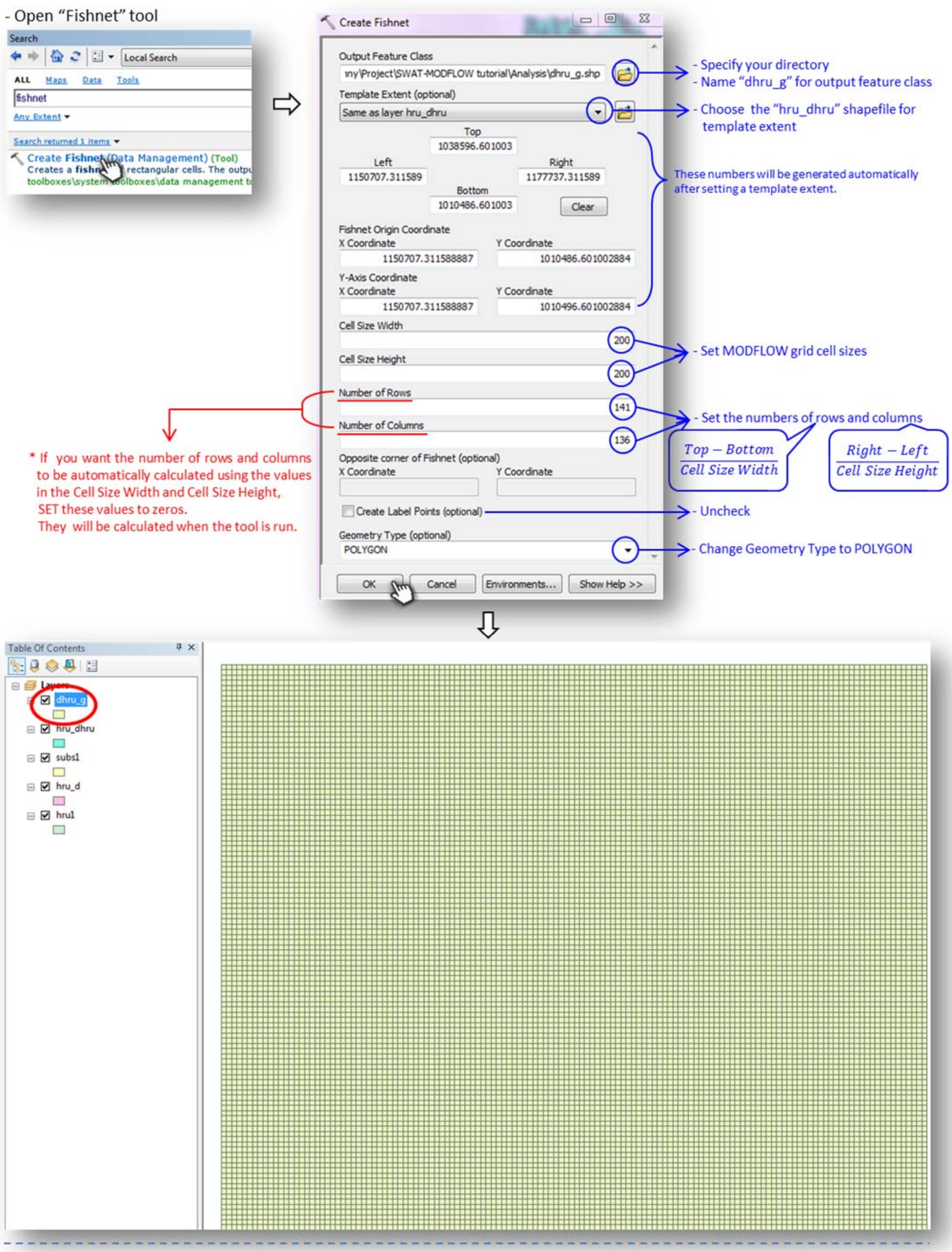
*grid_id*: ID of the MODFLOW grid cell (only cells intersecting DHRUs)
*grid_area*: Spatial Area ($m^2$) of the grid cell
*dhru_id*: ID of the DHRU
*overlap_area*: Overlap area ($m^2$) between the cell and the DHRU
*dhru_area*: Spatial area ($m^2$) of the DHRU

For example:

```
61838
19176
grid_id grid_area       dhru_id overlap_area    dhru_area
16      40000   27      3000    9900
16      40000   58      600     900
16      40000   63      1900    31500
17      40000   7       6000    7200
17      40000   27      6900    9900
17      40000   57      800     4500
17      40000   58      300     900
17      40000   63      800     31500
18      40000   57      400     4500
137     40000   1158    5600    76500
138     40000   1158    25100   76500
138     40000   1182    4500    11700
139     40000   1158    8600    76500
139     40000   1159    3300    272700
139     40000   1368    4200    9000
140     40000   1159    1400    272700
141     40000   1159    8300    272700
142     40000   1148    900     900
142     40000   1159    21800   272700
142     40000   1261    300     53100
143     40000   1145    900     900
143     40000   1146    900     900
143     40000   1155    3200    68400
143     40000   1159    900     272700
143     40000   1261    1500    53100
144     40000   1147    2700    5400
144     40000   1155    400     68400
144     40000   1156    900     900
144     40000   1157    700     7200
144     40000   1163    900     6300
145     40000   2356    1800    200700
145     40000   1147    2700    5400
145     40000   1157    1700    7200
152     40000   63      1100    31500
```

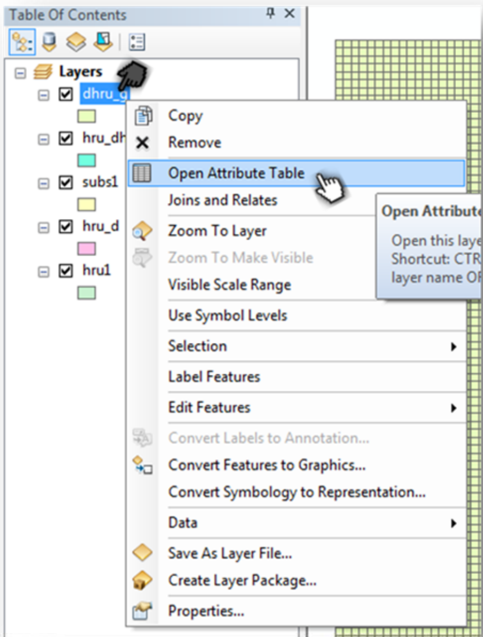
## 1. Create MODFLOW shapefile

① Create a fishnet of rectangular cells as MODFLOW Grid cells

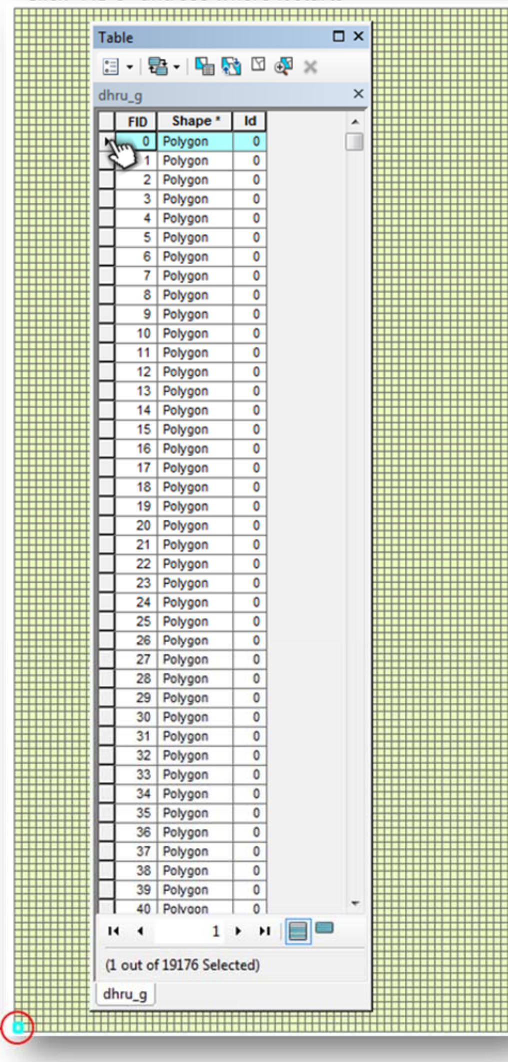


② Generate IDs of the MODFLOW grid cell (The origin of MODFLOW grid starts at upper left corner)

- Open the attribute table of the “dhru_g” shapefile

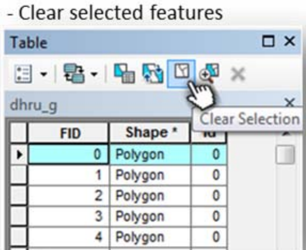


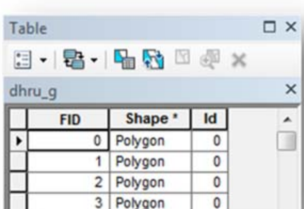

- Click “FID 0” and see where it starts



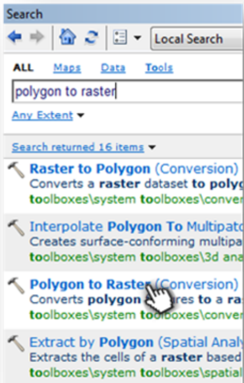

* The origin of the “dhru_g” shapefile starts at LOWER left corner

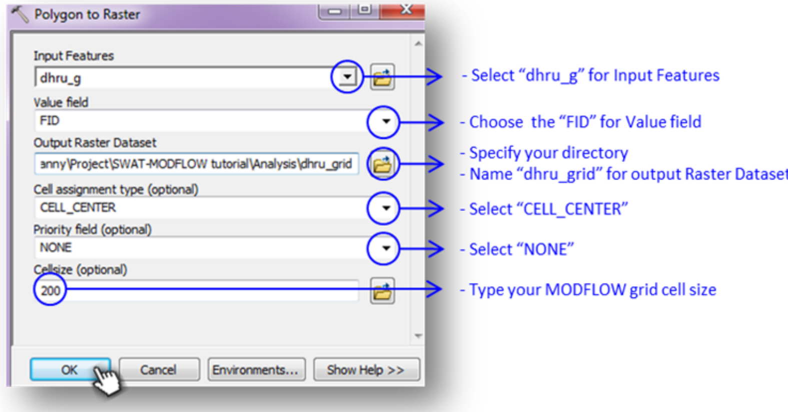
- Clear selected features

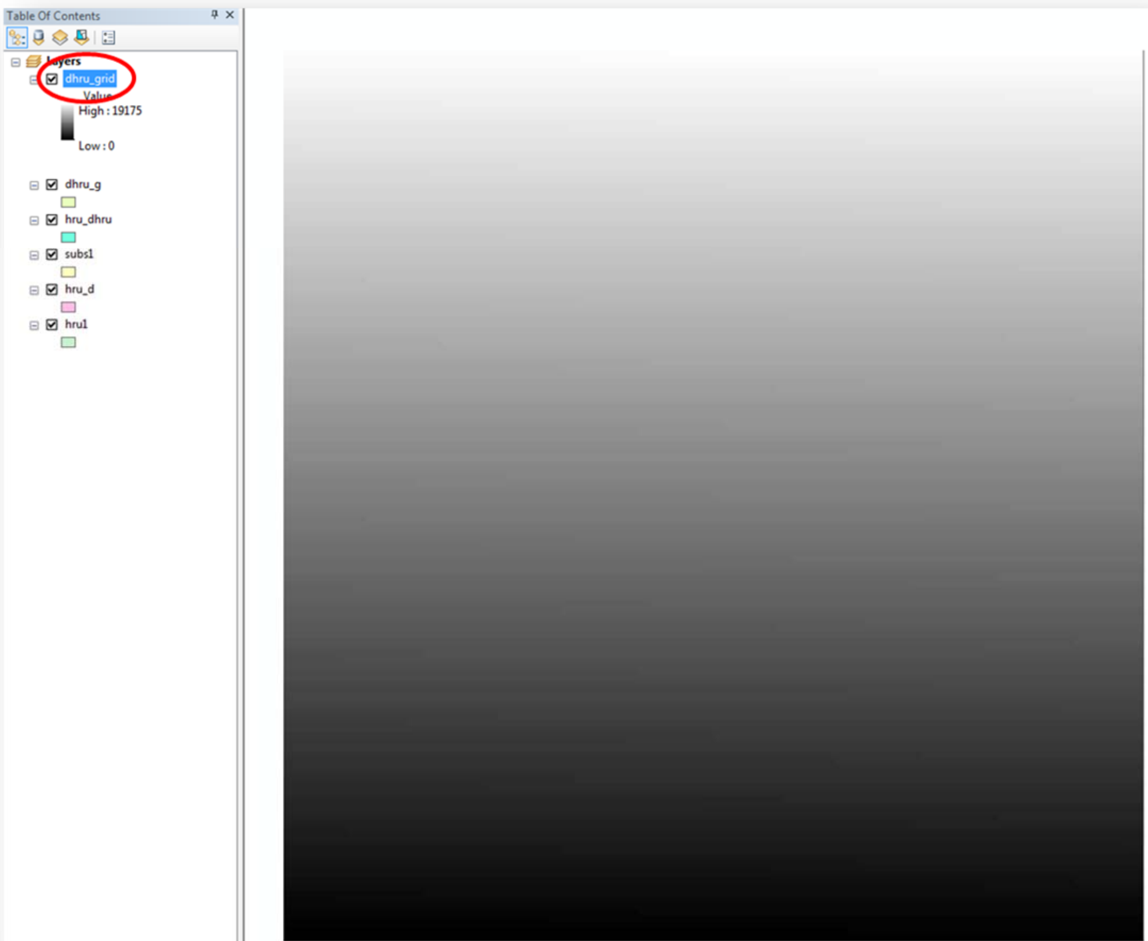


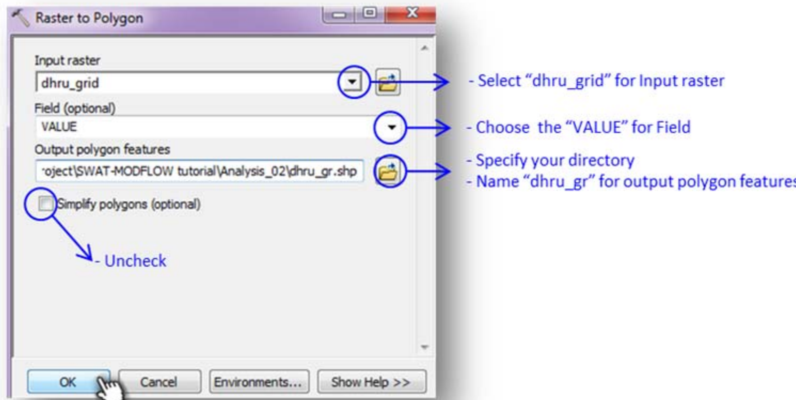
- Open the “Polygon to Raster” tool

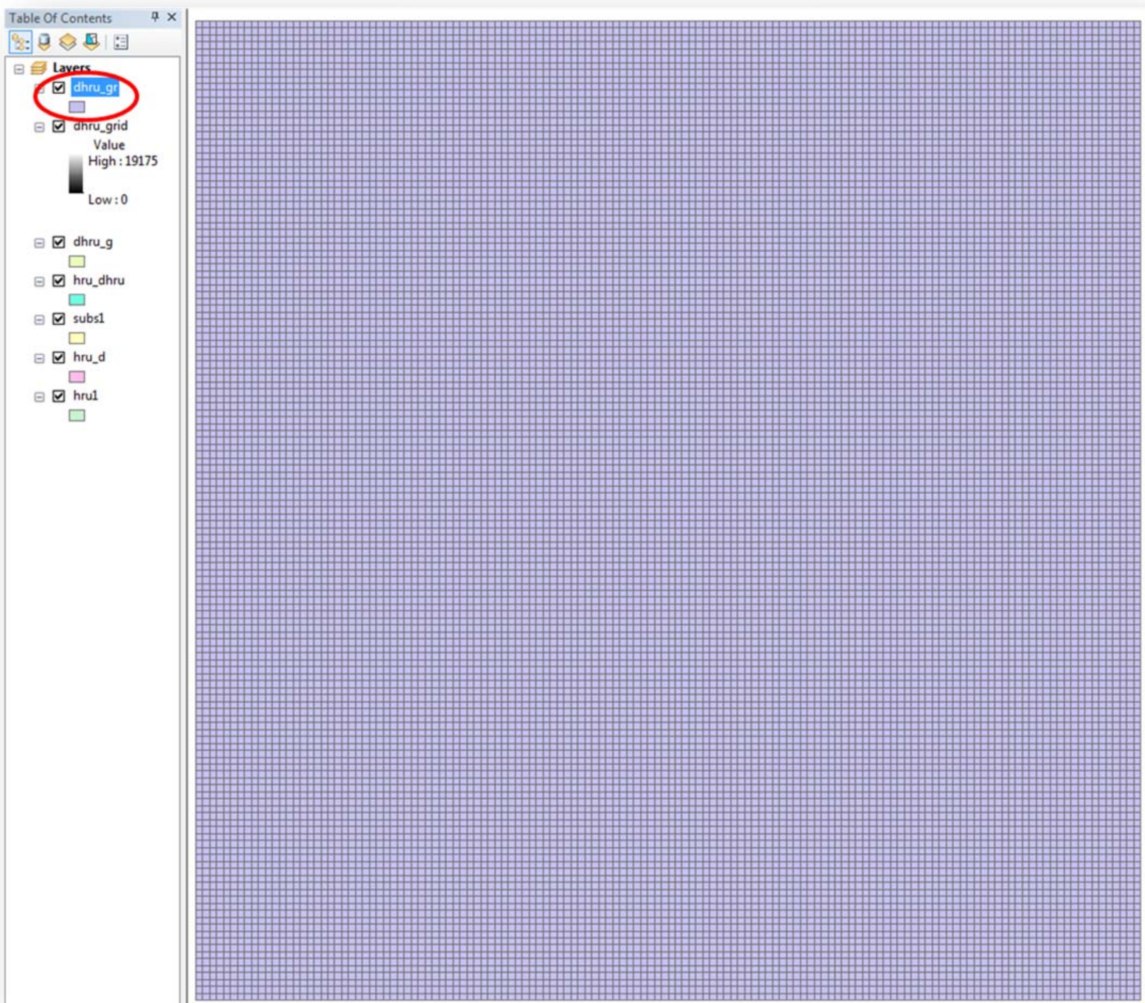




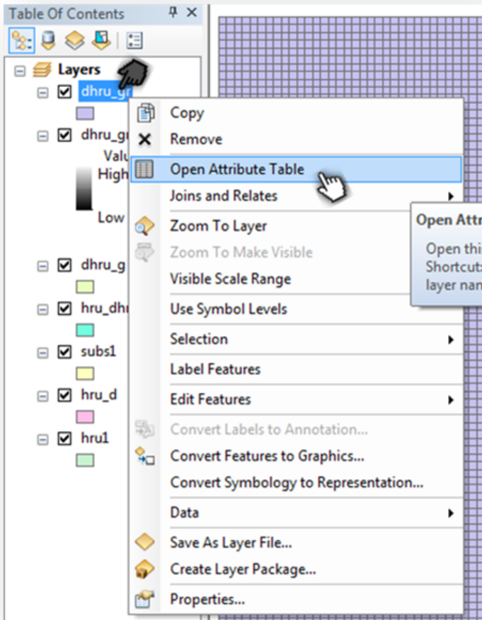



- Open the “Raster to Polygon” tool

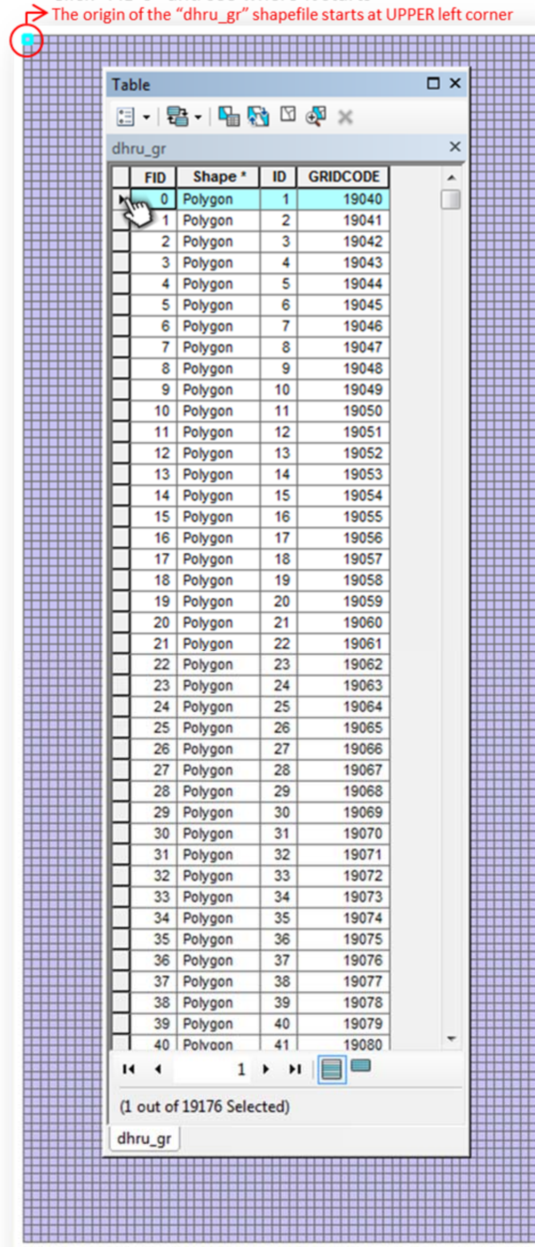



- Open the attribute table of the “dhru_gr” shapefile

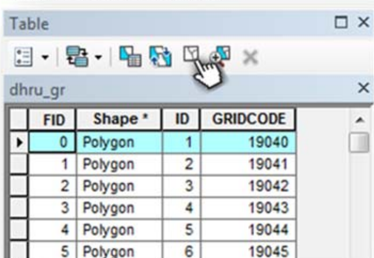


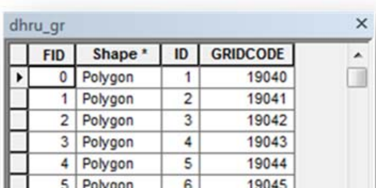

- Click “FID 0” and see where it starts

The origin of the “dhru_gr” shapefile starts at UPPER left corner

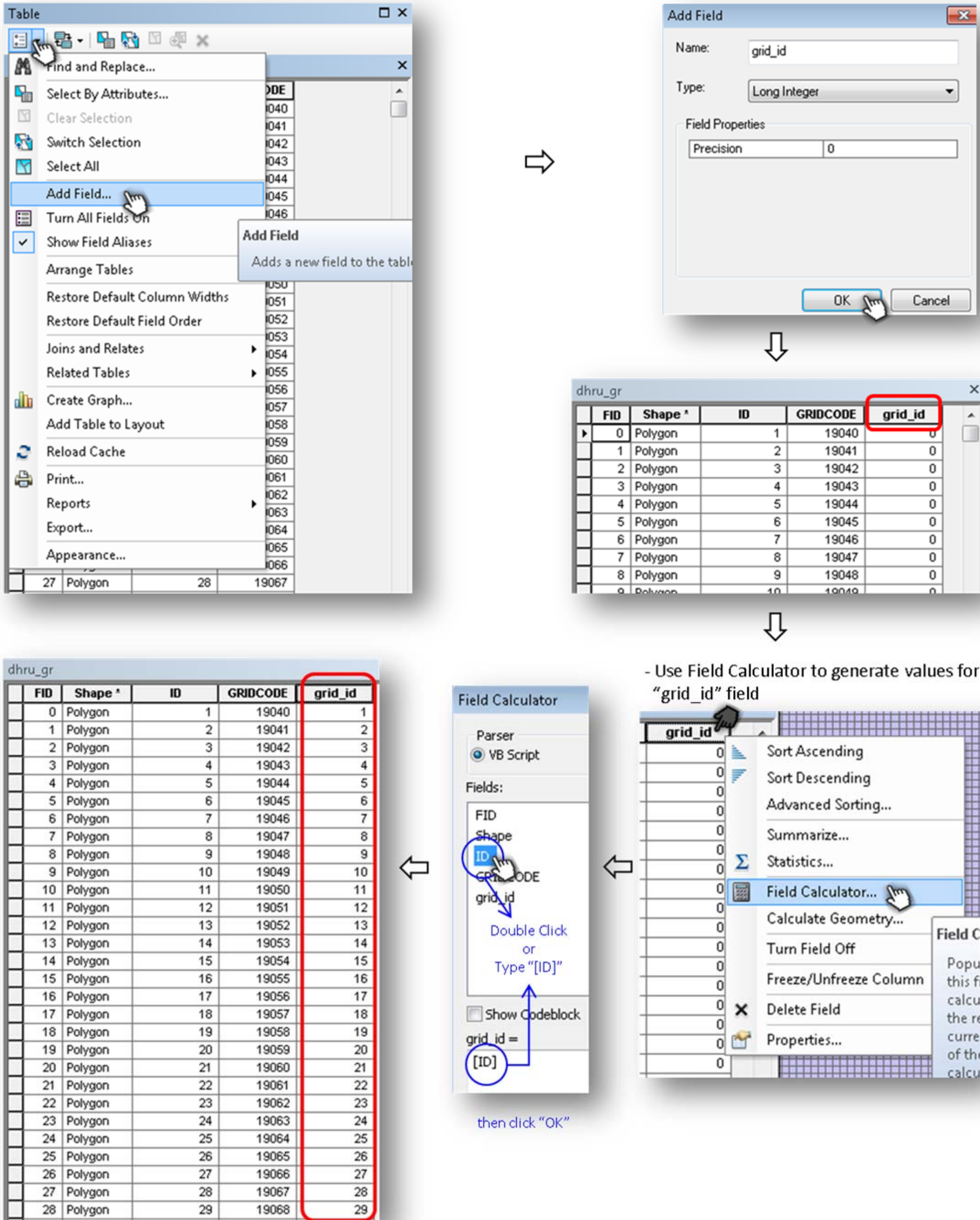



- Clear selected features



- 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)

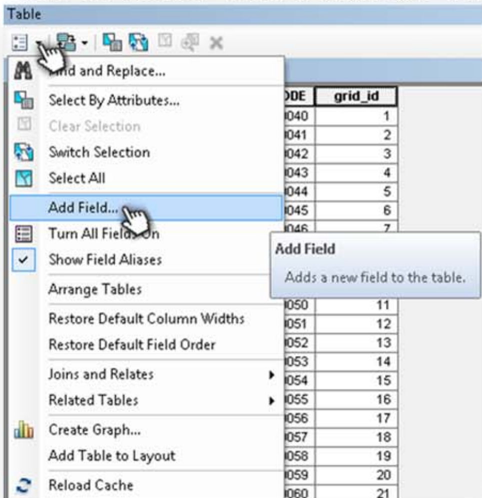



- Use Field Calculator to generate values for "grid_id" field

then click "OK"

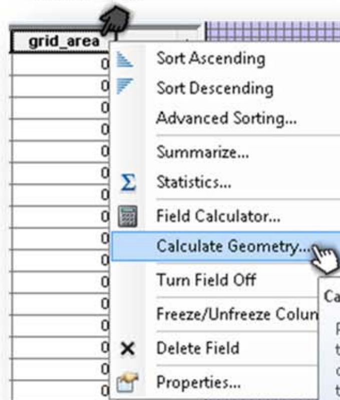
③ Calculate the spatial area of the grid cell

- Create the “grid_area” field with “long integer” type

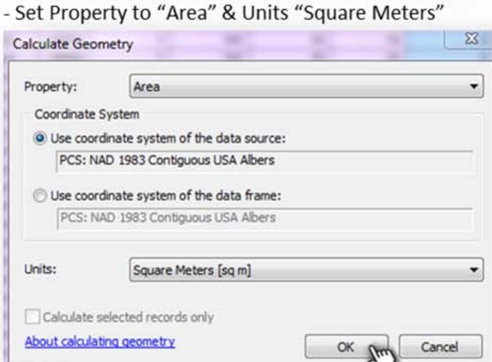


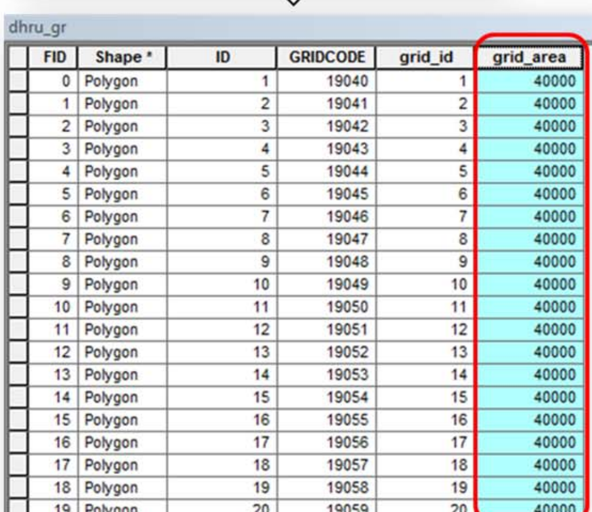



- Calculate the spatial area of the grid cell for “grid_id” field




- Set Property to “Area” & Units “Square Meters”



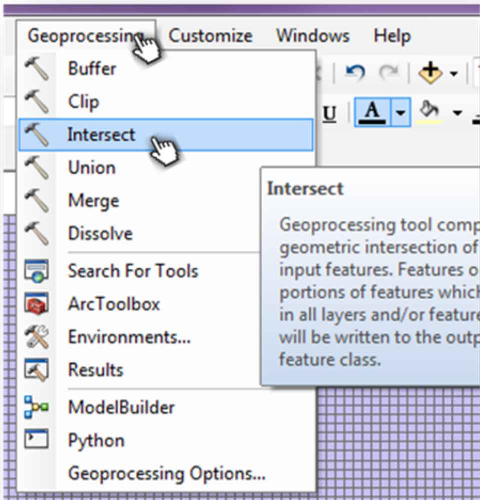


dhru_gr

| FID | Shape * | ID | GRIDCODE | grid_id | grid_area |
|---|---|---|---|---|---|
| 0 | Polygon | 1 | 19040 | 1 | 40000 |
| 1 | Polygon | 2 | 19041 | 2 | 40000 |
| 2 | Polygon | 3 | 19042 | 3 | 40000 |
| 3 | Polygon | 4 | 19043 | 4 | 40000 |
| 4 | Polygon | 5 | 19044 | 5 | 40000 |
| 5 | Polygon | 6 | 19045 | 6 | 40000 |
| 6 | Polygon | 7 | 19046 | 7 | 40000 |
| 7 | Polygon | 8 | 19047 | 8 | 40000 |
| 8 | Polygon | 9 | 19048 | 9 | 40000 |
| 9 | Polygon | 10 | 19049 | 10 | 40000 |
| 10 | Polygon | 11 | 19050 | 11 | 40000 |
| 11 | Polygon | 12 | 19051 | 12 | 40000 |
| 12 | Polygon | 13 | 19052 | 13 | 40000 |
| 13 | Polygon | 14 | 19053 | 14 | 40000 |
| 14 | Polygon | 15 | 19054 | 15 | 40000 |
| 15 | Polygon | 16 | 19055 | 16 | 40000 |
| 16 | Polygon | 17 | 19056 | 17 | 40000 |
| 17 | Polygon | 18 | 19057 | 18 | 40000 |
| 18 | Polygon | 19 | 19058 | 19 | 40000 |
| 19 | Polygon | 20 | 19059 | 20 | 40000 |

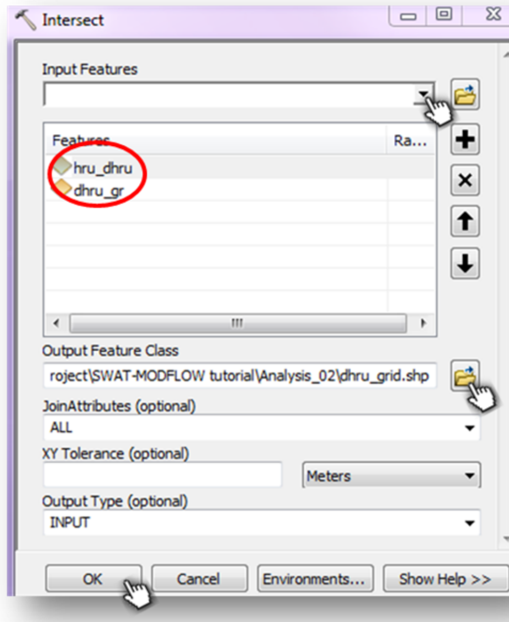
## 2. Intersect the “dhru_gr” shapefile with “hru_dhru” shapefile

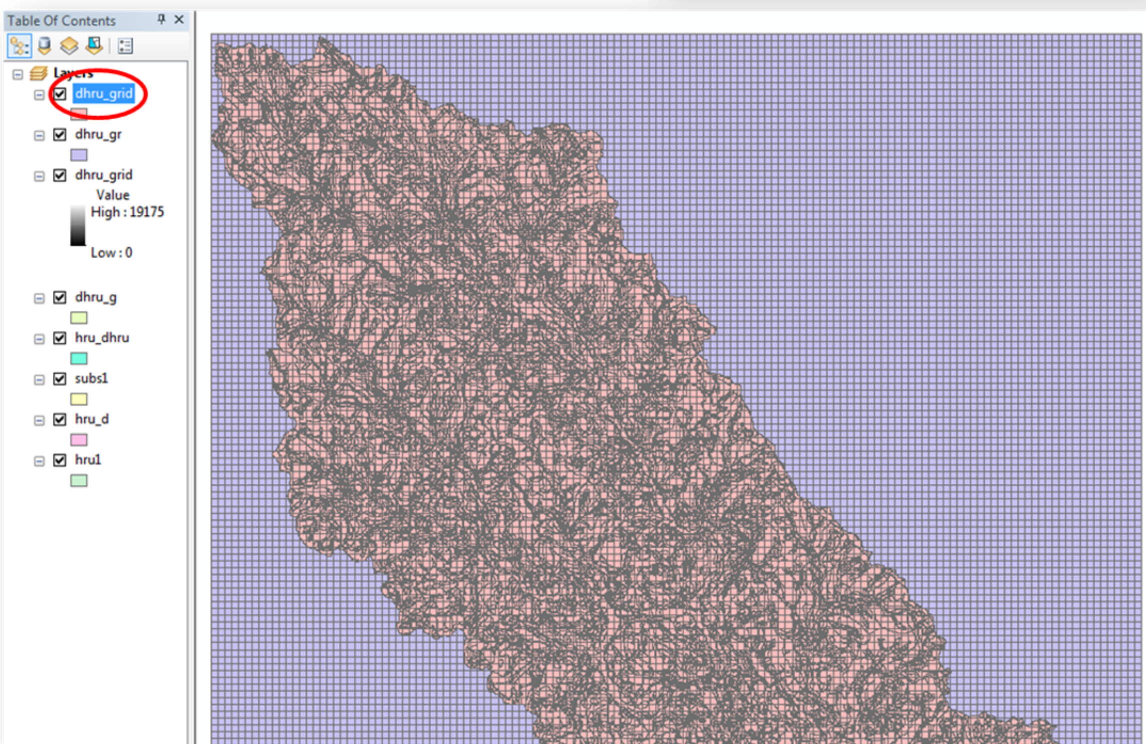
① Intersect the “dhru_gr” shapefile with “hru_dhru” shapefile

- Run Intersect tool



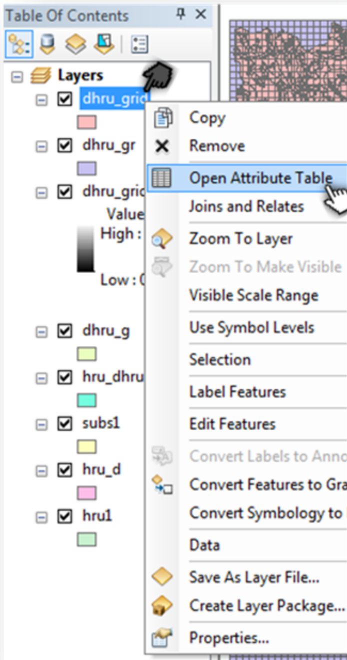

- Add the “hru_dhru” and “dhru_gr” shapefiles in Input Features
- Specify the output feature class name (dhru_grid) and directory

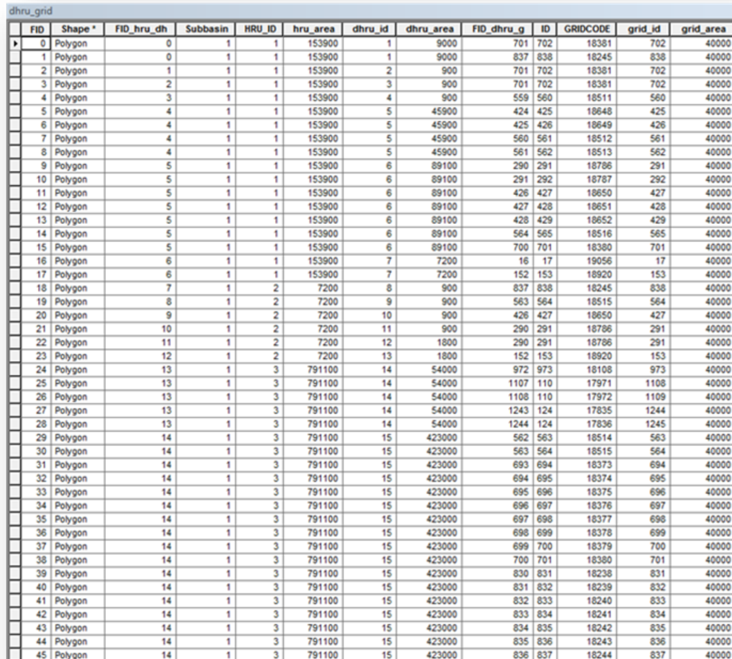


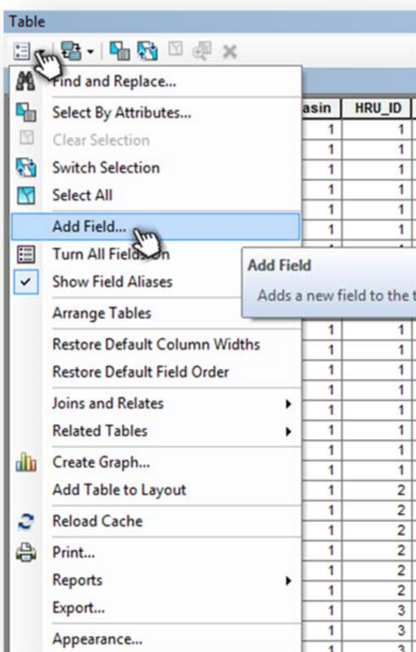



② Calculate the overlap area between Grid cells and DHRUs

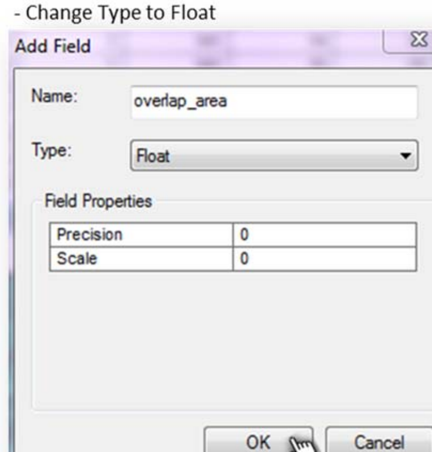
- Create the “overlap_area” field with the “Float” type



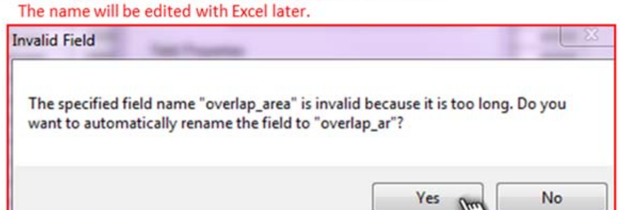



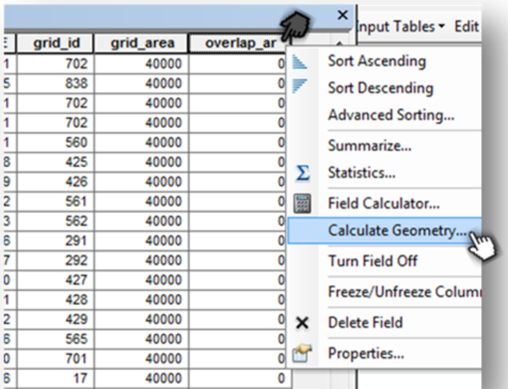

- Type “overlap_area” in Name
- Change Type to Float



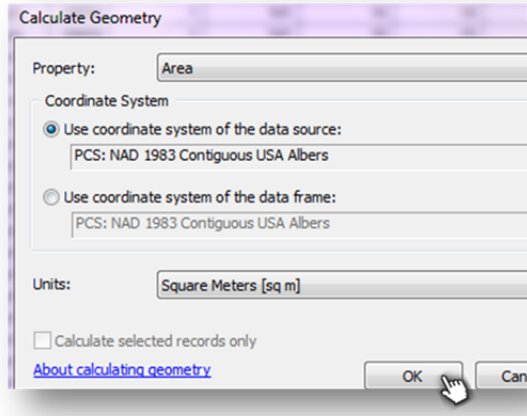

* Warning will be shown as the following figure. Click “Yes”.
The name will be edited with Excel later.



- Calculate the overlap area between Grid cells and DRHUs

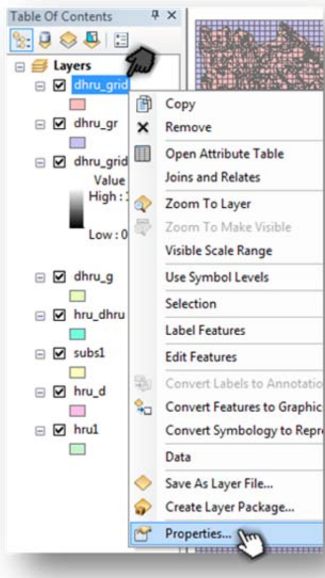


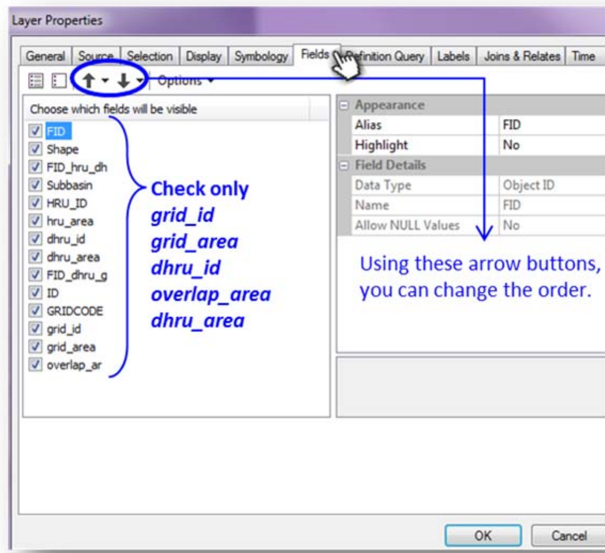

- Set Property to "Area" & Units "Square Meters"

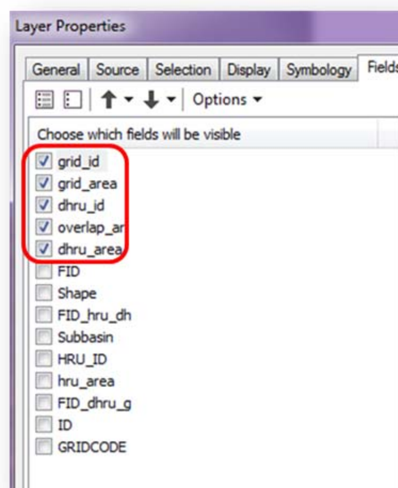



| Subbasin | HRU_ID | hru_area | dhru_id | dhru_area | FID_dhru_g | ID | GRIDCODE | grid_id | grid_area | overlap_ar |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 153900 | 1 | 9000 | 701 | 702 | 18381 | 702 | 40000 | 4500 |
| 1 | 1 | 153900 | 1 | 9000 | 837 | 838 | 18245 | 838 | 40000 | 4500 |
| 1 | 1 | 153900 | 2 | 900 | 701 | 702 | 18381 | 702 | 40000 | 900 |
| 1 | 1 | 153900 | 3 | 900 | 701 | 702 | 18381 | 702 | 40000 | 900 |
| 1 | 1 | 153900 | 4 | 900 | 559 | 560 | 18511 | 560 | 40000 | 900 |
| 1 | 1 | 153900 | 5 | 45900 | 424 | 425 | 18648 | 425 | 40000 | 9800 |
| 1 | 1 | 153900 | 5 | 45900 | 425 | 426 | 18649 | 426 | 40000 | 10900 |
| 1 | 1 | 153900 | 5 | 45900 | 560 | 561 | 18512 | 561 | 40000 | 15100 |
| 1 | 1 | 153900 | 5 | 45900 | 561 | 562 | 18513 | 562 | 40000 | 10100 |
| 1 | 1 | 153900 | 6 | 89100 | 290 | 291 | 18786 | 291 | 40000 | 16500 |
| 1 | 1 | 153900 | 6 | 89100 | 291 | 292 | 18787 | 292 | 40000 | 3300 |
| 1 | 1 | 153900 | 6 | 89100 | 426 | 427 | 18650 | 427 | 40000 | 7200 |
| 1 | 1 | 153900 | 6 | 89100 | 427 | 428 | 18651 | 428 | 40000 | 30300 |
| 1 | 1 | 153900 | 6 | 89100 | 428 | 429 | 18652 | 429 | 40000 | 14400 |
| 1 | 1 | 153900 | 6 | 89100 | 564 | 565 | 18516 | 565 | 40000 | 16800 |
| 1 | 1 | 153900 | 6 | 89100 | 700 | 701 | 18380 | 701 | 40000 | 600 |
| 1 | 1 | 153900 | 7 | 7200 | 16 | 17 | 19056 | 17 | 40000 | 6000 |
| 1 | 1 | 153900 | 7 | 7200 | 152 | 153 | 18920 | 153 | 40000 | 1200 |
| 1 | 2 | 7200 | 8 | 900 | 837 | 838 | 18245 | 838 | 40000 | 900 |
| 1 | 2 | 7200 | 9 | 900 | 563 | 564 | 18515 | 564 | 40000 | 900 |
| 1 | 2 | 7200 | 10 | 900 | 426 | 427 | 18650 | 427 | 40000 | 900 |
| 1 | 2 | 7200 | 11 | 900 | 290 | 291 | 18786 | 291 | 40000 | 900 |
| 1 | 2 | 7200 | 12 | 1800 | 290 | 291 | 18786 | 291 | 40000 | 1800 |
| 1 | 2 | 7200 | 13 | 1800 | 152 | 153 | 18920 | 153 | 40000 | 1800 |
| 1 | 3 | 791100 | 14 | 54000 | 972 | 973 | 18108 | 973 | 40000 | 6600 |
| 1 | 3 | 791100 | 14 | 54000 | 1107 | 110 | 17971 | 1108 | 40000 | 2400 |
| 1 | 3 | 791100 | 14 | 54000 | 1108 | 110 | 17972 | 1109 | 40000 | 24300 |
| 1 | 3 | 791100 | 14 | 54000 | 1243 | 124 | 17835 | 1244 | 40000 | 5100 |
| 1 | 3 | 791100 | 14 | 54000 | 1244 | 124 | 17836 | 1245 | 40000 | 15600 |
| 1 | 3 | 791100 | 15 | 423000 | 562 | 563 | 18514 | 563 | 40000 | 1700 |
| 1 | 3 | 791100 | 15 | 423000 | 563 | 564 | 18515 | 564 | 40000 | 2200 |
| 1 | 3 | 791100 | 15 | 423000 | 693 | 694 | 18373 | 694 | 40000 | 2400 |
| 1 | 3 | 791100 | 15 | 423000 | 694 | 695 | 18374 | 695 | 40000 | 14700 |
| 1 | 3 | 791100 | 15 | 423000 | 695 | 696 | 18375 | 696 | 40000 | 14100 |
| 1 | 3 | 791100 | 15 | 423000 | 696 | 697 | 18376 | 697 | 40000 | 1200 |
| 1 | 3 | 791100 | 15 | 423000 | 697 | 698 | 18377 | 698 | 40000 | 4500 |
| 1 | 3 | 791100 | 15 | 423000 | 698 | 699 | 18378 | 699 | 40000 | 35500 |
| 1 | 3 | 791100 | 15 | 423000 | 699 | 700 | 18379 | 700 | 40000 | 34700 |
| 1 | 3 | 791100 | 15 | 423000 | 700 | 701 | 18380 | 701 | 40000 | 8700 |
| 1 | 3 | 791100 | 15 | 423000 | 830 | 831 | 18238 | 831 | 40000 | 9900 |
| 1 | 3 | 791100 | 15 | 423000 | 831 | 832 | 18239 | 832 | 40000 | 38400 |
| 1 | 3 | 791100 | 15 | 423000 | 832 | 833 | 18240 | 833 | 40000 | 35600 |

③ Select only the necessary fields (You can either turn off or delete an unnecessary field)



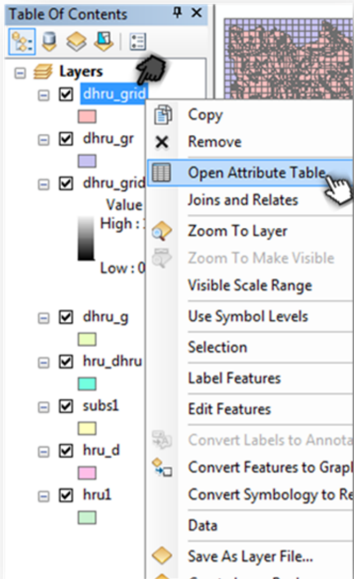

Then, click OK.

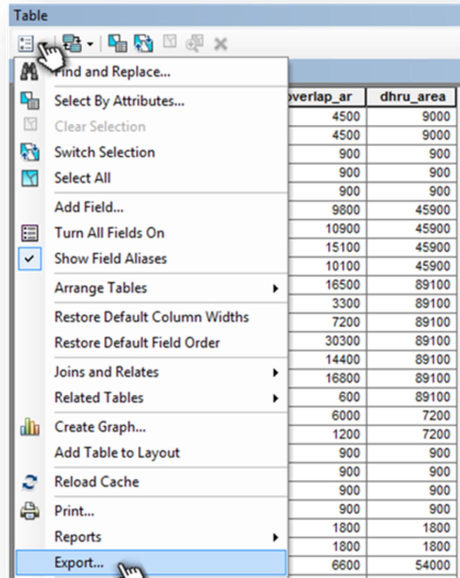
dhru_grid

| grid_id | grid_area | dhru_id | overlap_ar | dhru_area |
|---|---|---|---|---|
| 702 | 40000 | 1 | 4500 | 9000 |
| 838 | 40000 | 1 | 4500 | 9000 |
| 702 | 40000 | 2 | 900 | 900 |
| 702 | 40000 | 3 | 900 | 900 |
| 560 | 40000 | 4 | 900 | 900 |
| 425 | 40000 | 5 | 9800 | 45900 |
| 426 | 40000 | 5 | 10900 | 45900 |
| 561 | 40000 | 5 | 15100 | 45900 |
| 562 | 40000 | 5 | 10100 | 45900 |
| 291 | 40000 | 6 | 16500 | 89100 |
| 292 | 40000 | 6 | 3300 | 89100 |
| 427 | 40000 | 6 | 7200 | 89100 |
| 428 | 40000 | 6 | 30300 | 89100 |
| 429 | 40000 | 6 | 14400 | 89100 |
| 565 | 40000 | 6 | 16800 | 89100 |
| 701 | 40000 | 6 | 600 | 89100 |
| 17 | 40000 | 7 | 6000 | 7200 |
| 153 | 40000 | 7 | 1200 | 7200 |
| 838 | 40000 | 8 | 900 | 900 |
| 564 | 40000 | 9 | 900 | 900 |
| 427 | 40000 | 10 | 900 | 900 |
| 291 | 40000 | 11 | 900 | 900 |
| 291 | 40000 | 12 | 1800 | 1800 |
| 153 | 40000 | 13 | 1800 | 1800 |
| 973 | 40000 | 14 | 6600 | 54000 |
| 1108 | 40000 | 14 | 2400 | 54000 |
| 1109 | 40000 | 14 | 24300 | 54000 |
| 1244 | 40000 | 14 | 5100 | 54000 |
| 1245 | 40000 | 14 | 15600 | 54000 |
| 563 | 40000 | 15 | 1700 | 423000 |
| 564 | 40000 | 15 | 2200 | 423000 |

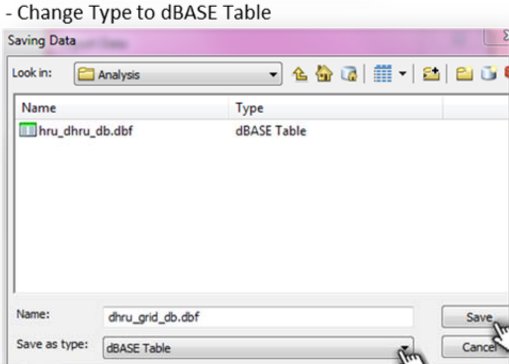
④ Provide text file: **dhru_grid** (This file is sorted by the “grid_id”, then by “dhru_id”)

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

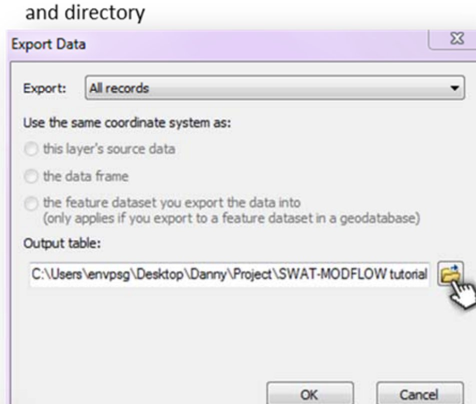



- Change Type to dBASE Table



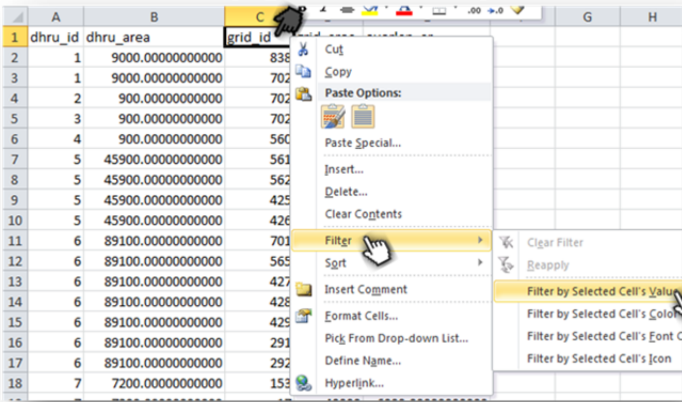

- Specify the output table name (dhru_grid_db) and directory

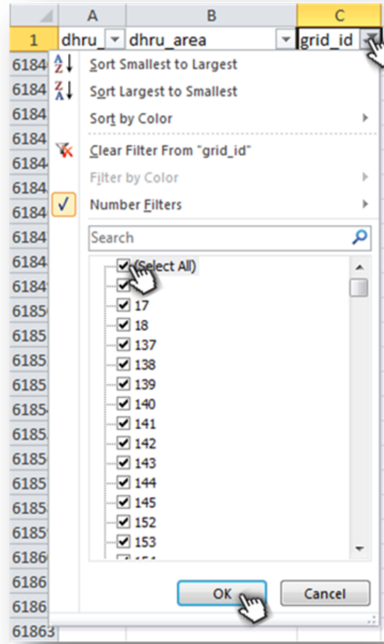


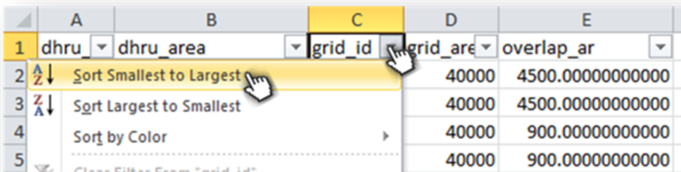

- Open the “dhru_grid_db” file with Excel

| | A | B | C | D | E |
|---|---|---|---|---|---|
| 1 | dhru_id | dhru_area | grid_id | grid_area | overlap_ar |
| 2 | 1 | 9000.00000000000 | 838 | 40000 | 4500.00000000000 |
| 3 | 1 | 9000.00000000000 | 702 | 40000 | 4500.00000000000 |
| 4 | 2 | 900.00000000000 | 702 | 40000 | 900.00000000000 |
| 5 | 3 | 900.00000000000 | 702 | 40000 | 900.00000000000 |
| 6 | 4 | 900.00000000000 | 560 | 40000 | 900.00000000000 |
| 7 | 5 | 45900.00000000000 | 561 | 40000 | 15100.00000000000 |
| 8 | 5 | 45900.00000000000 | 562 | 40000 | 10100.00000000000 |
| 9 | 5 | 45900.00000000000 | 425 | 40000 | 9800.00000000000 |
| 10 | 5 | 45900.00000000000 | 426 | 40000 | 10900.00000000000 |
| 11 | 6 | 89100.00000000000 | 701 | 40000 | 600.00000000000 |
| 12 | 6 | 89100.00000000000 | 565 | 40000 | 16800.00000000000 |
| 13 | 6 | 89100.00000000000 | 427 | 40000 | 7200.00000000000 |
| 14 | 6 | 89100.00000000000 | 428 | 40000 | 30300.00000000000 |

- Use Filter and Sort the “grid_id” column in ascending order



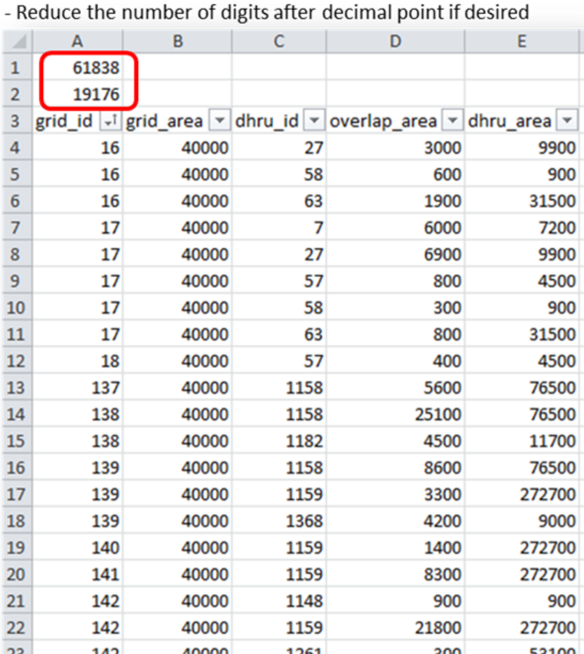




- Change the order of the columns and correct the column names

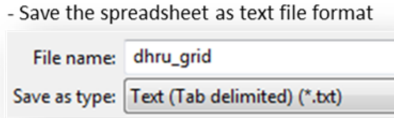
- Insert two rows at the top of the spreadsheet and write the number of lines with information (starting on Line 4) and number of MODFLOW grid cells

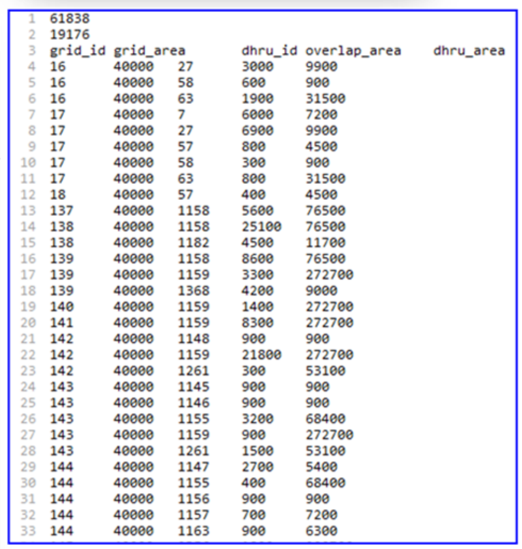
- Reduce the number of digits after decimal point if desired



| | A | B | C | D | E |
|---|---|---|---|---|---|
| 1 | 61838 | | | | |
| 2 | 19176 | | | | |
| 3 | grid_id | grid_area | dhru_id | overlap_area | dhru_area |
| 4 | 16 | 40000 | 27 | 3000 | 9900 |
| 5 | 16 | 40000 | 58 | 600 | 900 |
| 6 | 16 | 40000 | 63 | 1900 | 31500 |
| 7 | 17 | 40000 | 7 | 6000 | 7200 |
| 8 | 17 | 40000 | 27 | 6900 | 9900 |
| 9 | 17 | 40000 | 57 | 800 | 4500 |
| 10 | 17 | 40000 | 58 | 300 | 900 |
| 11 | 17 | 40000 | 63 | 800 | 31500 |
| 12 | 18 | 40000 | 57 | 400 | 4500 |
| 13 | 137 | 40000 | 1158 | 5600 | 76500 |
| 14 | 138 | 40000 | 1158 | 25100 | 76500 |
| 15 | 138 | 40000 | 1182 | 4500 | 11700 |
| 16 | 139 | 40000 | 1158 | 8600 | 76500 |
| 17 | 139 | 40000 | 1159 | 3300 | 272700 |
| 18 | 139 | 40000 | 1368 | 4200 | 9000 |
| 19 | 140 | 40000 | 1159 | 1400 | 272700 |
| 20 | 141 | 40000 | 1159 | 8300 | 272700 |
| 21 | 142 | 40000 | 1148 | 900 | 900 |
| 22 | 142 | 40000 | 1159 | 21800 | 272700 |
| 23 | 142 | 40000 | 1261 | 300 | 53100 |

- Save the spreadsheet as text file format



```
1  61838
2  19176
3  grid_id grid_area       dhru_id overlap_area    dhru_area
4  16      40000   27      3000    9900
5  16      40000   58      600     900
6  16      40000   63      1900    31500
7  17      40000   7       6000    7200
8  17      40000   27      6900    9900
9  17      40000   57      800     4500
10 17      40000   58      300     900
11 17      40000   63      800     31500
12 18      40000   57      400     4500
13 137     40000   1158    5600    76500
14 138     40000   1158    25100   76500
15 138     40000   1182    4500    11700
16 139     40000   1158    8600    76500
17 139     40000   1159    3300    272700
18 139     40000   1368    4200    9000
19 140     40000   1159    1400    272700
20 141     40000   1159    8300    272700
21 142     40000   1148    900     900
22 142     40000   1159    21800   272700
23 142     40000   1261    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   1261    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   1163    900     6300
```

### 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:

<u>At the top of the file</u>:

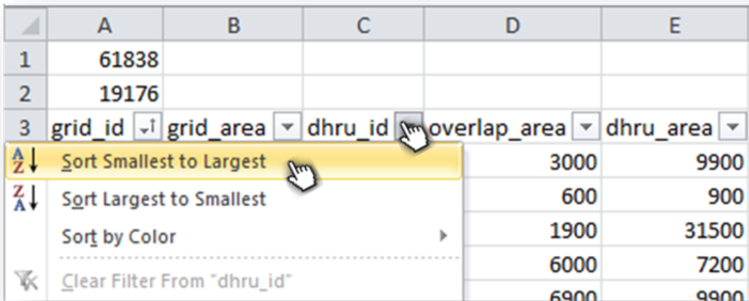
> *Number of lines with information (starting on Line 6)*
> *Number of DHRUs*
> *Number of rows (in the MODFLOW grid)*
> *Number of columns (in the MODFLOW grid)*

<u>For example</u>:

```
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
10 560     40000   4       900     900
11 425     40000   5       9800    45900
12 426     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
18 428     40000   6       30300   89100
19 429     40000   6       14400   89100
20 565     40000   6       16800   89100
21 701     40000   6       600     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      6600    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    423000
36 564     40000   15      2200    423000
37 694     40000   15      2400    423000
38 695     40000   15      14700   423000
39 696     40000   15      14100   423000
```

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




⇩

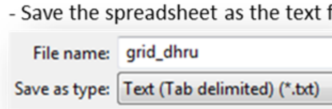
- Insert two more rows above the row with the names of the columns

- Keep the value in 1st row, change the value to the number of DHRUs 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.

| | A | B | C | D | E |
|---|---|---|---|---|---|
| 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 | 560 | 40000 | 4 | 900 | 900 |
| 11 | 425 | 40000 | 5 | 9800 | 45900 |
| 12 | 426 | 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 | 428 | 40000 | 6 | 30300 | 89100 |
| 19 | 429 | 40000 | 6 | 14400 | 89100 |
| 20 | 565 | 40000 | 6 | 16800 | 89100 |
| 21 | 701 | 40000 | 6 | 600 | 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 | 6600 | 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 |

⇨

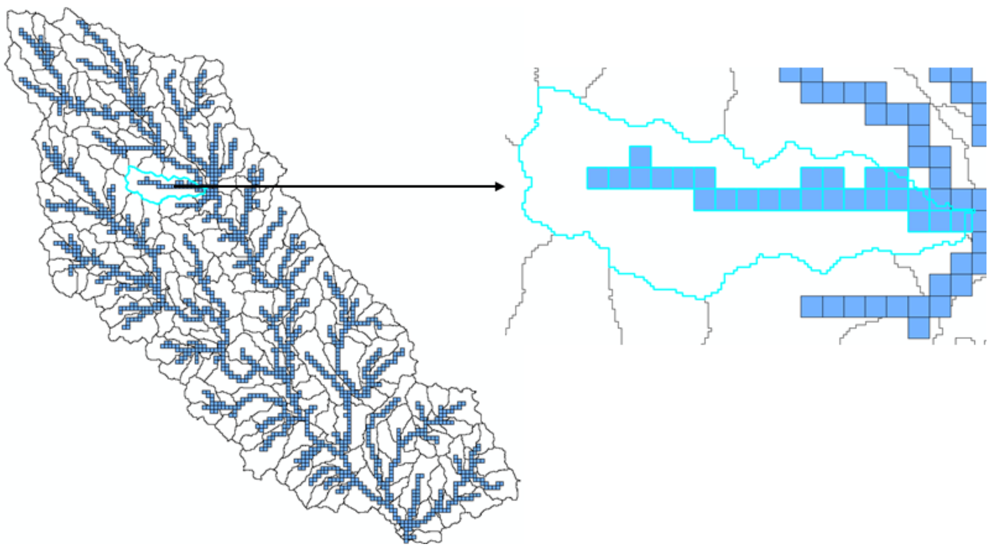
- Save the spreadsheet as the text file format




```
61838
27396
141
136
grid_id grid_area	dhru_id overlap_area	dhru_area
702	40000	1	4500	9000
838	40000	1	4500	9000
702	40000	2	900	900
702	40000	3	900	900
560	40000	4	900	900
425	40000	5	9800	45900
426	40000	5	10900	45900
561	40000	5	15100	45900
562	40000	5	10100	45900
291	40000	6	16500	89100
292	40000	6	3300	89100
427	40000	6	7200	89100
428	40000	6	30300	89100
429	40000	6	14400	89100
565	40000	6	16800	89100
701	40000	6	600	89100
17	40000	7	6000	7200
153	40000	7	1200	7200
838	40000	8	900	900
564	40000	9	900	900
427	40000	10	900	900
291	40000	11	900	900
291	40000	12	1800	1800
153	40000	13	1800	1800
973	40000	14	6600	54000
1108	40000	14	2400	54000
1109	40000	14	24300	54000
1244	40000	14	5100	54000
1245	40000	14	15600	54000
563	40000	15	1700	423000
564	40000	15	2200	423000
694	40000	15	2400	423000
695	40000	15	14700	423000
696	40000	15	14100	423000
697	40000	15	1200	423000
698	40000	15	4500	423000
```

### 4.1.4 Linkage between MODFLOW River Cells and SWAT Subbasins

The MODFLOW River Cells are connected with the SWAT subbasins so that water exchanged between the aquifer and the stream network can be added to / subtracted from the water in the SWAT subbasin channels. The set of River Cells in each subbasin are identified, so that the volumes of groundwater-surface water exchange can be summed and added to / subtracted from the subbasin channel water. The following map shows the set of River Cells for one of the subbasins in the LRW SWAT model.



File to create: **river_grid**.

<u>At the top of the file</u>:

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

<u>Then, the following columns</u> (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.

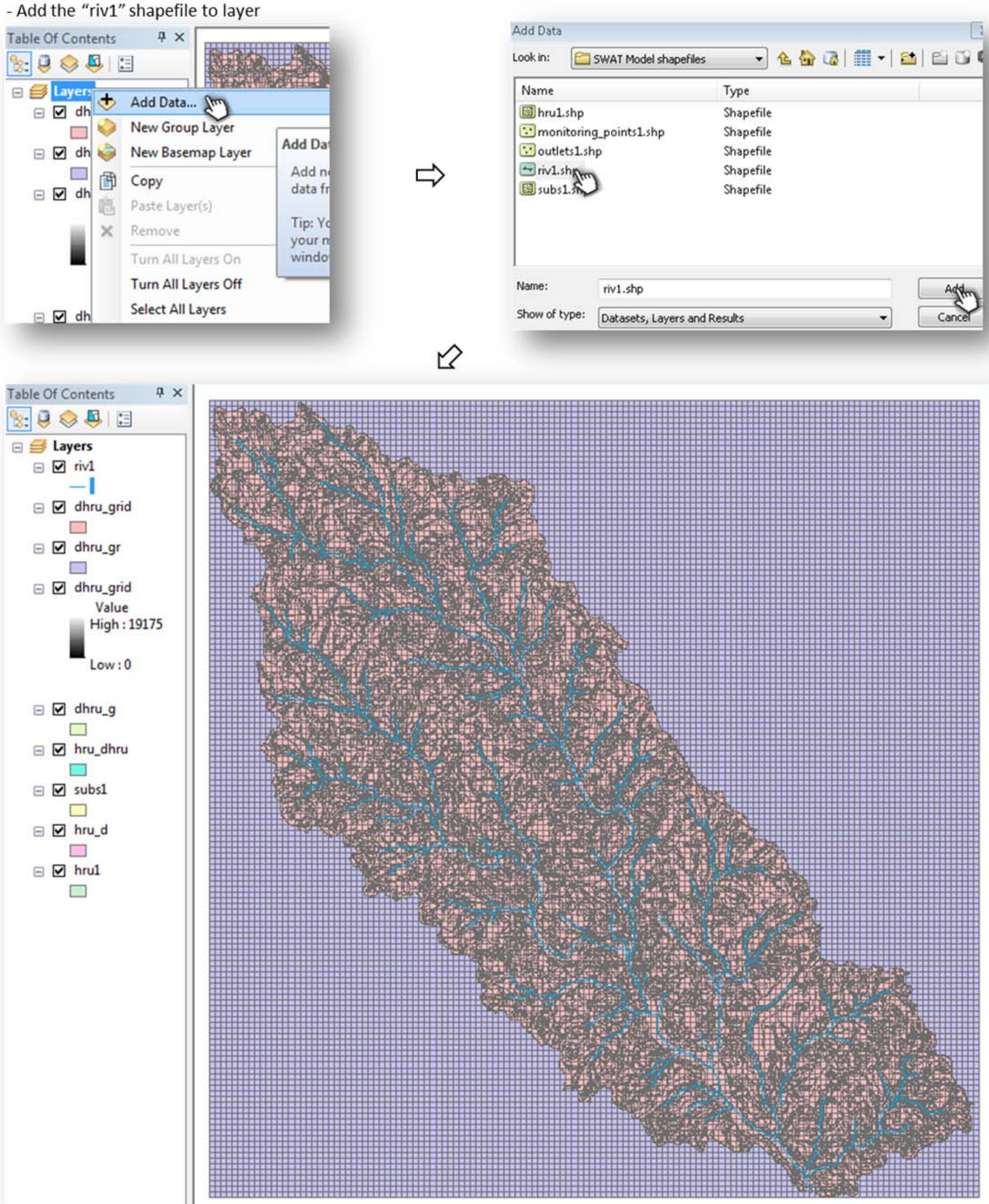
For example:

```
1921
grid_id subbasin        rgrid_len
564     1       197.78200000000
565     1       199.70600000000
701     1       203.13700000000
702     1       42.42640000000
820     9       7.07105000000
821     9       144.85300000000
838     1       123.64000000000
838     57      151.92400000000
957     9       100.71100000000
958     9       259.70600000000
974     57      40.35530000000
975     57      277.63500000000
976     57      102.78200000000
1094    9       28.28430000000
1095    9       287.99000000000
1096    9       14.14210000000
1098    17      153.64000000000
1112    57      215.20800000000
1113    57      114.85300000000
1232    9       257.99000000000
1234    17      245.56300000000
1249    57      173.13700000000
1250    57      245.56300000000
1251    57      102.07100000000
1368    9       60.35530000000
1369    9       217.27900000000
1371    49      35.35530000000
1371    25      55.00000000000
1371    17      282.63500000000
1372    25      119.85300000000
```

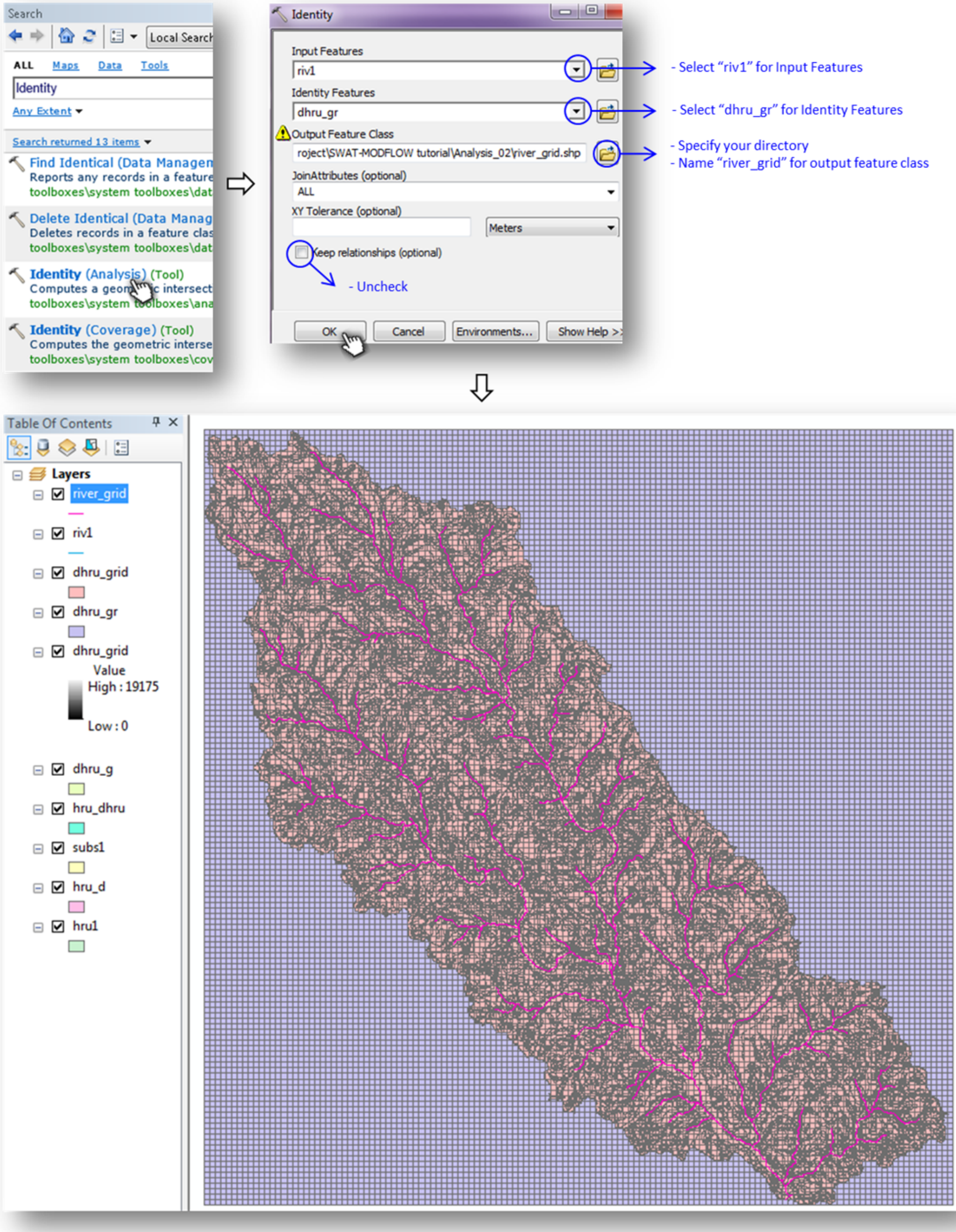
# 1. Compute SWAT stream network in the MODFLOW Grid

① Calculate each length of the stream in each grid cell

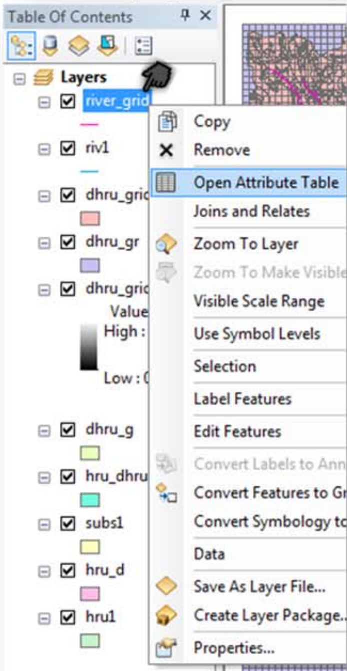
- Add the “riv1” shapefile to layer

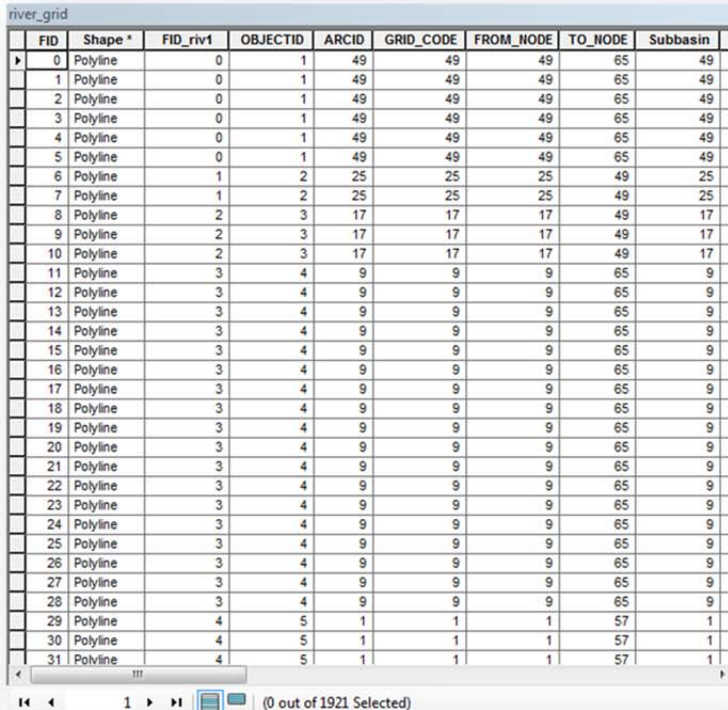


- Open “Identity” tool



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

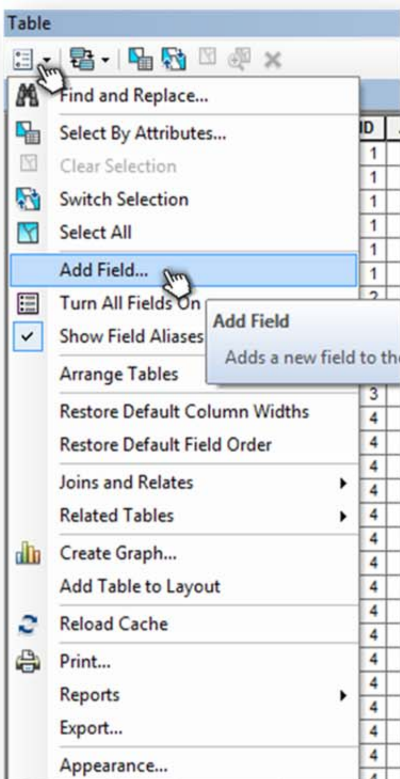


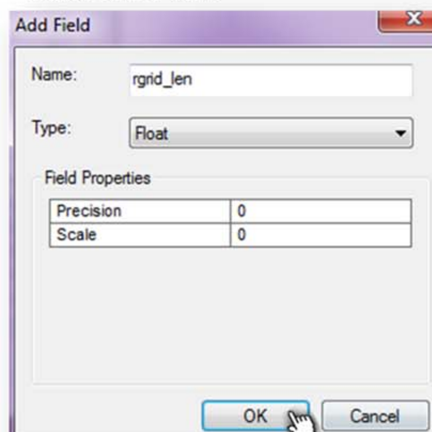
river_grid

| FID | Shape * | FID_riv1 | OBJECTID | ARCID | GRID_CODE | FROM_NODE | TO_NODE | Subbasin |
|---|---|---|---|---|---|---|---|---|
| 0 | Polyline | 0 | 1 | 49 | 49 | 49 | 65 | 49 |
| 1 | Polyline | 0 | 1 | 49 | 49 | 49 | 65 | 49 |
| 2 | Polyline | 0 | 1 | 49 | 49 | 49 | 65 | 49 |
| 3 | Polyline | 0 | 1 | 49 | 49 | 49 | 65 | 49 |
| 4 | Polyline | 0 | 1 | 49 | 49 | 49 | 65 | 49 |
| 5 | Polyline | 0 | 1 | 49 | 49 | 49 | 65 | 49 |
| 6 | Polyline | 1 | 2 | 25 | 25 | 25 | 49 | 25 |
| 7 | Polyline | 1 | 2 | 25 | 25 | 25 | 49 | 25 |
| 8 | Polyline | 2 | 3 | 17 | 17 | 17 | 49 | 17 |
| 9 | Polyline | 2 | 3 | 17 | 17 | 17 | 49 | 17 |
| 10 | Polyline | 2 | 3 | 17 | 17 | 17 | 49 | 17 |
| 11 | Polyline | 3 | 4 | 9 | 9 | 9 | 65 | 9 |
| 12 | Polyline | 3 | 4 | 9 | 9 | 9 | 65 | 9 |
| 13 | Polyline | 3 | 4 | 9 | 9 | 9 | 65 | 9 |
| 14 | Polyline | 3 | 4 | 9 | 9 | 9 | 65 | 9 |
| 15 | Polyline | 3 | 4 | 9 | 9 | 9 | 65 | 9 |
| 16 | Polyline | 3 | 4 | 9 | 9 | 9 | 65 | 9 |
| 17 | Polyline | 3 | 4 | 9 | 9 | 9 | 65 | 9 |
| 18 | Polyline | 3 | 4 | 9 | 9 | 9 | 65 | 9 |
| 19 | Polyline | 3 | 4 | 9 | 9 | 9 | 65 | 9 |
| 20 | Polyline | 3 | 4 | 9 | 9 | 9 | 65 | 9 |
| 21 | Polyline | 3 | 4 | 9 | 9 | 9 | 65 | 9 |
| 22 | Polyline | 3 | 4 | 9 | 9 | 9 | 65 | 9 |
| 23 | Polyline | 3 | 4 | 9 | 9 | 9 | 65 | 9 |
| 24 | Polyline | 3 | 4 | 9 | 9 | 9 | 65 | 9 |
| 25 | Polyline | 3 | 4 | 9 | 9 | 9 | 65 | 9 |
| 26 | Polyline | 3 | 4 | 9 | 9 | 9 | 65 | 9 |
| 27 | Polyline | 3 | 4 | 9 | 9 | 9 | 65 | 9 |
| 28 | Polyline | 3 | 4 | 9 | 9 | 9 | 65 | 9 |
| 29 | Polyline | 4 | 5 | 1 | 1 | 1 | 57 | 1 |
| 30 | Polyline | 4 | 5 | 1 | 1 | 1 | 57 | 1 |
| 31 | Polyline | 4 | 5 | 1 | 1 | 1 | 57 | 1 |

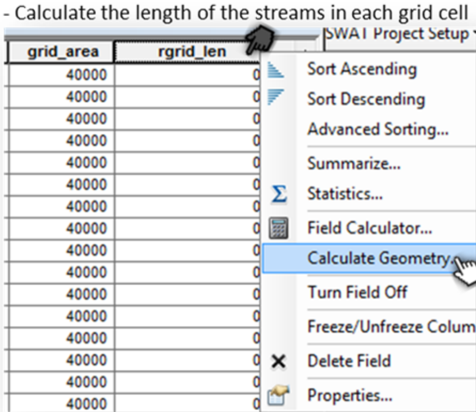
(0 out of 1921 Selected)



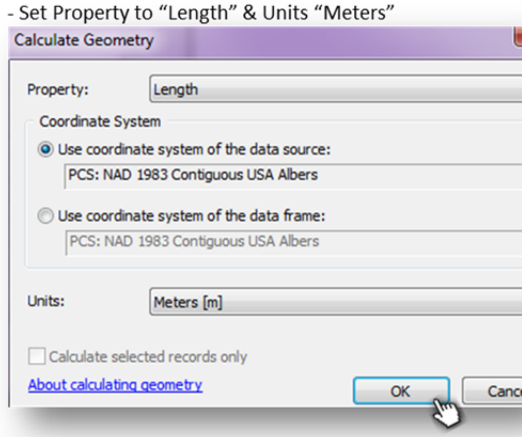

- Type “rgrid_len” in Name
- Change Type to Float

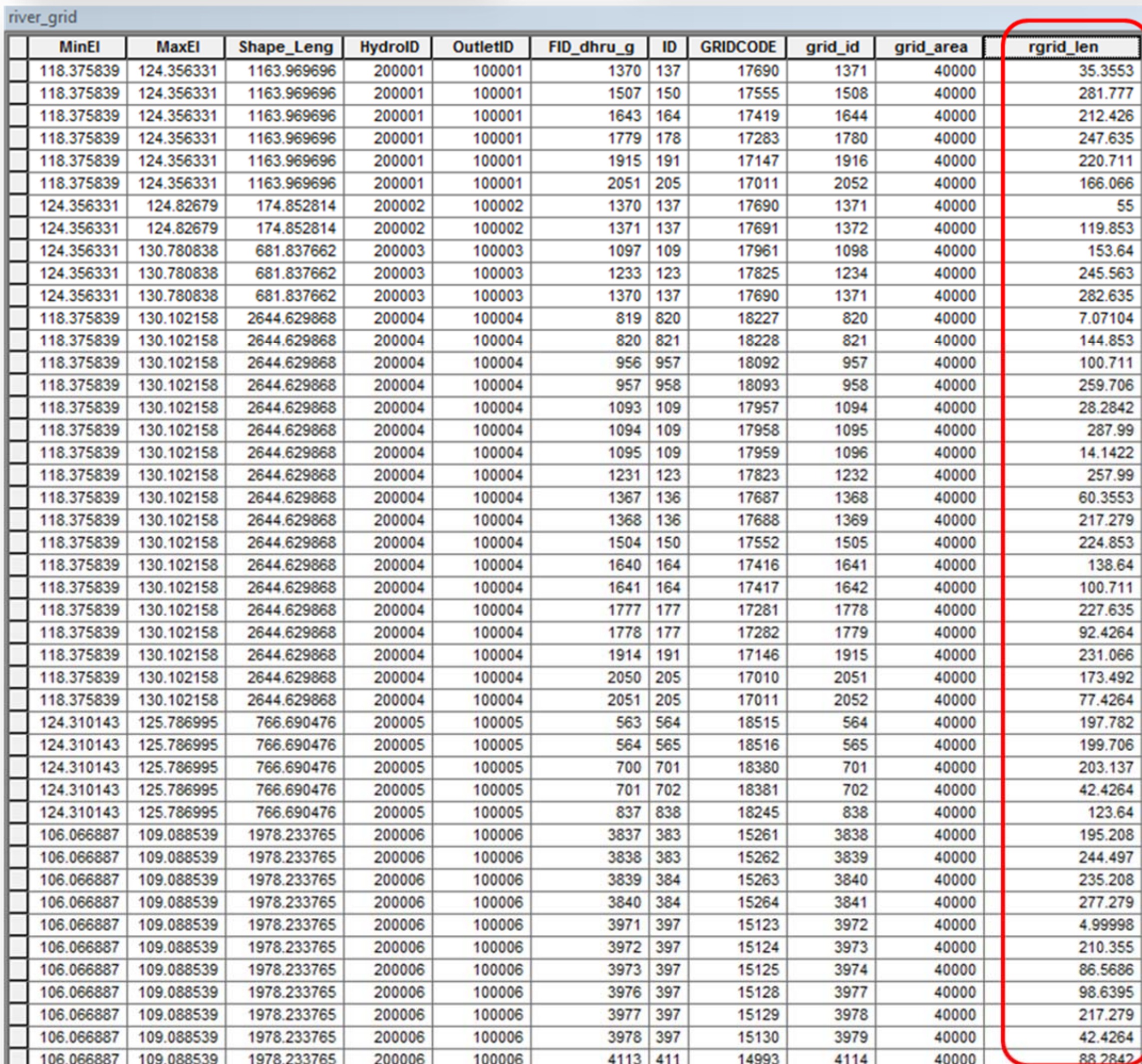


- Calculate the length of the streams in each grid cell




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

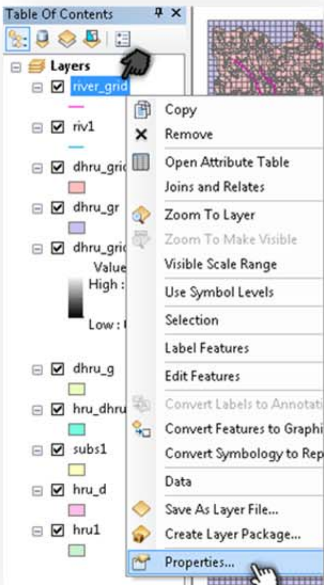


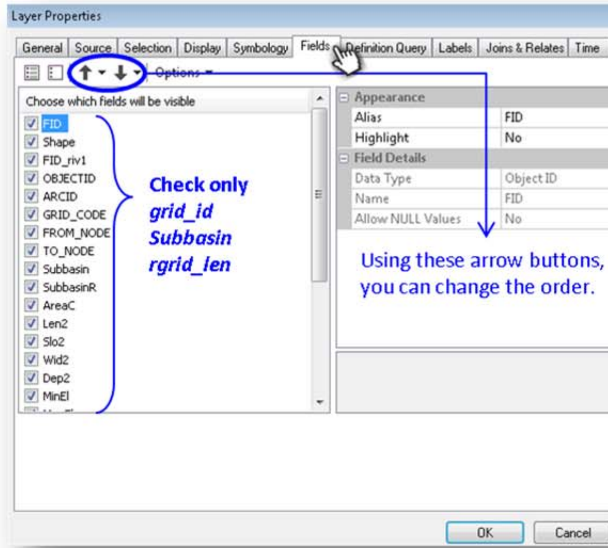



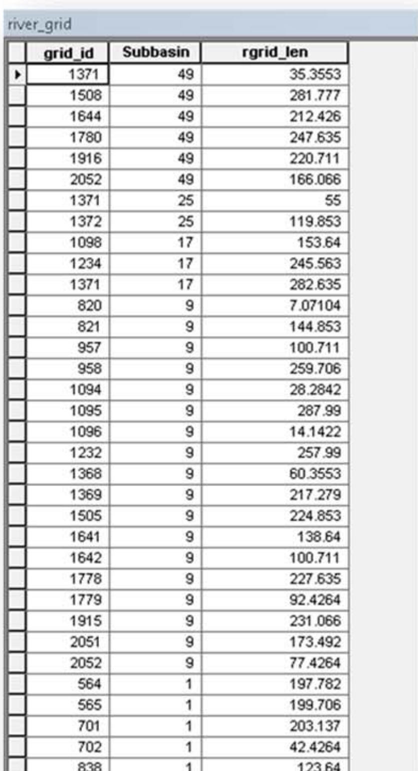
river_grid

| MinEl | MaxEl | Shape_Leng | HydroID | OutletID | FID_dhru_g | ID | GRIDCODE | grid_id | grid_area | rgrid_len |
|---|---|---|---|---|---|---|---|---|---|---|
| 118.375839 | 124.356331 | 1163.969696 | 200001 | 100001 | 1370 | 137 | 17690 | 1371 | 40000 | 35.3553 |
| 118.375839 | 124.356331 | 1163.969696 | 200001 | 100001 | 1507 | 150 | 17555 | 1508 | 40000 | 281.777 |
| 118.375839 | 124.356331 | 1163.969696 | 200001 | 100001 | 1643 | 164 | 17419 | 1644 | 40000 | 212.426 |
| 118.375839 | 124.356331 | 1163.969696 | 200001 | 100001 | 1779 | 178 | 17283 | 1780 | 40000 | 247.635 |
| 118.375839 | 124.356331 | 1163.969696 | 200001 | 100001 | 1915 | 191 | 17147 | 1916 | 40000 | 220.711 |
| 118.375839 | 124.356331 | 1163.969696 | 200001 | 100001 | 2051 | 205 | 17011 | 2052 | 40000 | 166.066 |
| 124.356331 | 124.82679 | 174.852814 | 200002 | 100002 | 1370 | 137 | 17690 | 1371 | 40000 | 55 |
| 124.356331 | 124.82679 | 174.852814 | 200002 | 100002 | 1371 | 137 | 17691 | 1372 | 40000 | 119.853 |
| 124.356331 | 130.780838 | 681.837662 | 200003 | 100003 | 1097 | 109 | 17961 | 1098 | 40000 | 153.64 |
| 124.356331 | 130.780838 | 681.837662 | 200003 | 100003 | 1233 | 123 | 17825 | 1234 | 40000 | 245.563 |
| 124.356331 | 130.780838 | 681.837662 | 200003 | 100003 | 1370 | 137 | 17690 | 1371 | 40000 | 282.635 |
| 118.375839 | 130.102158 | 2644.629868 | 200004 | 100004 | 819 | 820 | 18227 | 820 | 40000 | 7.07104 |
| 118.375839 | 130.102158 | 2644.629868 | 200004 | 100004 | 820 | 821 | 18228 | 821 | 40000 | 144.853 |
| 118.375839 | 130.102158 | 2644.629868 | 200004 | 100004 | 956 | 957 | 18092 | 957 | 40000 | 100.711 |
| 118.375839 | 130.102158 | 2644.629868 | 200004 | 100004 | 957 | 958 | 18093 | 958 | 40000 | 259.706 |
| 118.375839 | 130.102158 | 2644.629868 | 200004 | 100004 | 1093 | 109 | 17957 | 1094 | 40000 | 28.2842 |
| 118.375839 | 130.102158 | 2644.629868 | 200004 | 100004 | 1094 | 109 | 17958 | 1095 | 40000 | 287.99 |
| 118.375839 | 130.102158 | 2644.629868 | 200004 | 100004 | 1095 | 109 | 17959 | 1096 | 40000 | 14.1422 |
| 118.375839 | 130.102158 | 2644.629868 | 200004 | 100004 | 1231 | 123 | 17823 | 1232 | 40000 | 257.99 |
| 118.375839 | 130.102158 | 2644.629868 | 200004 | 100004 | 1367 | 136 | 17687 | 1368 | 40000 | 60.3553 |
| 118.375839 | 130.102158 | 2644.629868 | 200004 | 100004 | 1368 | 136 | 17688 | 1369 | 40000 | 217.279 |
| 118.375839 | 130.102158 | 2644.629868 | 200004 | 100004 | 1504 | 150 | 17552 | 1505 | 40000 | 224.853 |
| 118.375839 | 130.102158 | 2644.629868 | 200004 | 100004 | 1640 | 164 | 17416 | 1641 | 40000 | 138.64 |
| 118.375839 | 130.102158 | 2644.629868 | 200004 | 100004 | 1641 | 164 | 17417 | 1642 | 40000 | 100.711 |
| 118.375839 | 130.102158 | 2644.629868 | 200004 | 100004 | 1777 | 177 | 17281 | 1778 | 40000 | 227.635 |
| 118.375839 | 130.102158 | 2644.629868 | 200004 | 100004 | 1778 | 177 | 17282 | 1779 | 40000 | 92.4264 |
| 118.375839 | 130.102158 | 2644.629868 | 200004 | 100004 | 1914 | 191 | 17146 | 1915 | 40000 | 231.066 |
| 118.375839 | 130.102158 | 2644.629868 | 200004 | 100004 | 2050 | 205 | 17010 | 2051 | 40000 | 173.492 |
| 118.375839 | 130.102158 | 2644.629868 | 200004 | 100004 | 2051 | 205 | 17011 | 2052 | 40000 | 77.4264 |
| 124.310143 | 125.786995 | 766.690476 | 200005 | 100005 | 563 | 564 | 18515 | 564 | 40000 | 197.782 |
| 124.310143 | 125.786995 | 766.690476 | 200005 | 100005 | 564 | 565 | 18516 | 565 | 40000 | 199.706 |
| 124.310143 | 125.786995 | 766.690476 | 200005 | 100005 | 700 | 701 | 18380 | 701 | 40000 | 203.137 |
| 124.310143 | 125.786995 | 766.690476 | 200005 | 100005 | 701 | 702 | 18381 | 702 | 40000 | 42.4264 |
| 124.310143 | 125.786995 | 766.690476 | 200005 | 100005 | 837 | 838 | 18245 | 838 | 40000 | 123.64 |
| 106.066887 | 109.088539 | 1978.233765 | 200006 | 100006 | 3837 | 383 | 15261 | 3838 | 40000 | 195.208 |
| 106.066887 | 109.088539 | 1978.233765 | 200006 | 100006 | 3838 | 383 | 15262 | 3839 | 40000 | 244.497 |
| 106.066887 | 109.088539 | 1978.233765 | 200006 | 100006 | 3839 | 384 | 15263 | 3840 | 40000 | 235.208 |
| 106.066887 | 109.088539 | 1978.233765 | 200006 | 100006 | 3840 | 384 | 15264 | 3841 | 40000 | 277.279 |
| 106.066887 | 109.088539 | 1978.233765 | 200006 | 100006 | 3971 | 397 | 15123 | 3972 | 40000 | 4.99998 |
| 106.066887 | 109.088539 | 1978.233765 | 200006 | 100006 | 3972 | 397 | 15124 | 3973 | 40000 | 210.355 |
| 106.066887 | 109.088539 | 1978.233765 | 200006 | 100006 | 3973 | 397 | 15125 | 3974 | 40000 | 86.5686 |
| 106.066887 | 109.088539 | 1978.233765 | 200006 | 100006 | 3976 | 397 | 15128 | 3977 | 40000 | 98.6395 |
| 106.066887 | 109.088539 | 1978.233765 | 200006 | 100006 | 3977 | 397 | 15129 | 3978 | 40000 | 217.279 |
| 106.066887 | 109.088539 | 1978.233765 | 200006 | 100006 | 3978 | 397 | 15130 | 3979 | 40000 | 42.4264 |
| 106.066887 | 109.088539 | 1978.233765 | 200006 | 100006 | 4113 | 411 | 14993 | 4114 | 40000 | 88.2842 |

② Select only the necessary fields (You can either turn off or delete unnecessary fields)

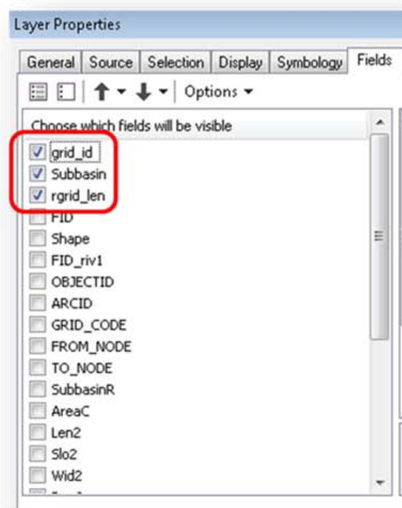


river_grid

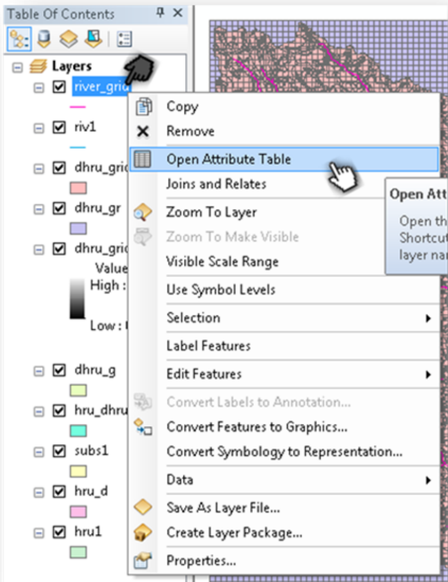
| grid_id | Subbasin | rgrid_len |
|---|---|---|
| 1371 | 49 | 35.3553 |
| 1508 | 49 | 281.777 |
| 1644 | 49 | 212.426 |
| 1780 | 49 | 247.635 |
| 1916 | 49 | 220.711 |
| 2052 | 49 | 166.066 |
| 1371 | 25 | 55 |
| 1372 | 25 | 119.853 |
| 1098 | 17 | 153.64 |
| 1234 | 17 | 245.563 |
| 1371 | 17 | 282.635 |
| 820 | 9 | 7.07104 |
| 821 | 9 | 144.853 |
| 957 | 9 | 100.711 |
| 958 | 9 | 259.706 |
| 1094 | 9 | 28.2842 |
| 1095 | 9 | 287.99 |
| 1096 | 9 | 14.1422 |
| 1232 | 9 | 257.99 |
| 1368 | 9 | 60.3553 |
| 1369 | 9 | 217.279 |
| 1505 | 9 | 224.853 |
| 1641 | 9 | 138.64 |
| 1642 | 9 | 100.711 |
| 1778 | 9 | 227.635 |
| 1779 | 9 | 92.4264 |
| 1915 | 9 | 231.066 |
| 2051 | 9 | 173.492 |
| 2052 | 9 | 77.4264 |
| 564 | 1 | 197.782 |
| 565 | 1 | 199.706 |
| 701 | 1 | 203.137 |
| 702 | 1 | 42.4264 |
| 838 | 1 | 123.64 |

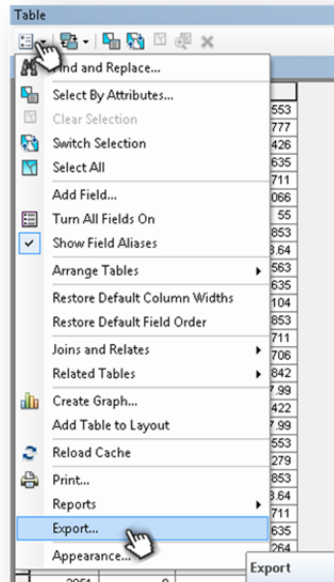



Then, click OK.

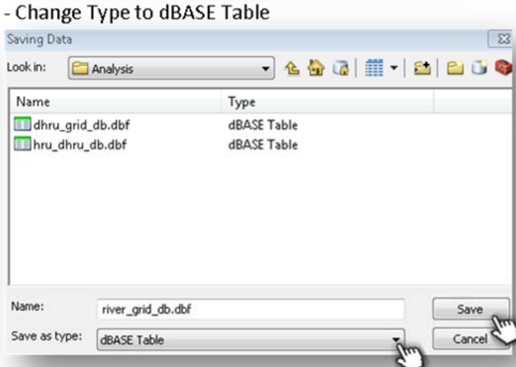
③ Provide text file: **river_grid**

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

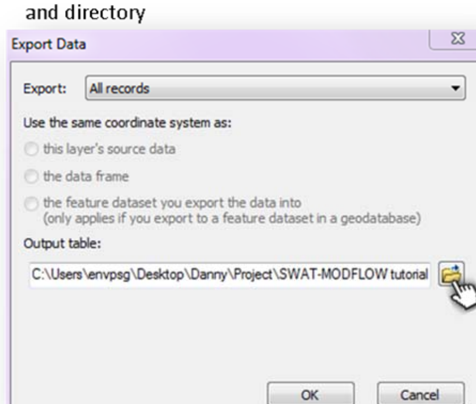


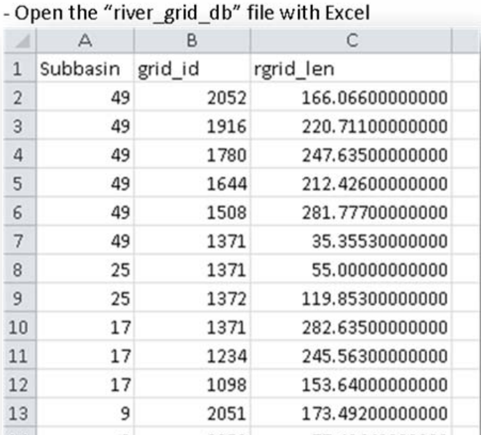

- Change Type to dBASE Table




- Specify the output table name (river_grid_db) and directory

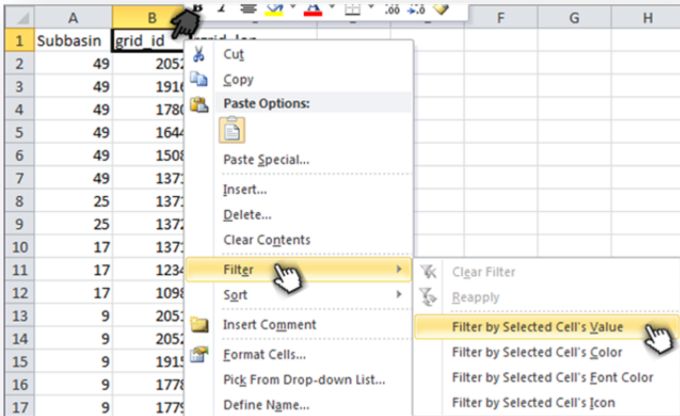


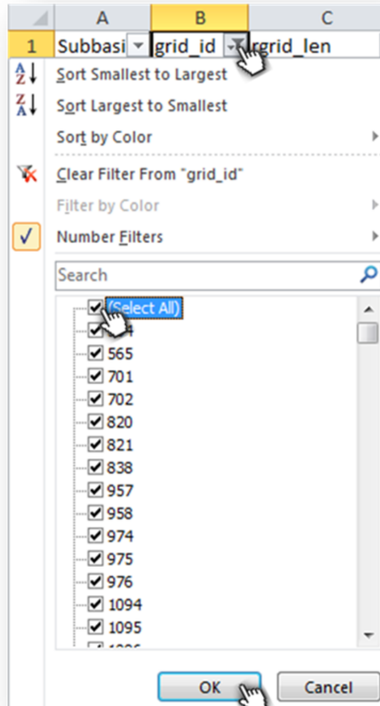

- Open the “river_grid_db” file with Excel

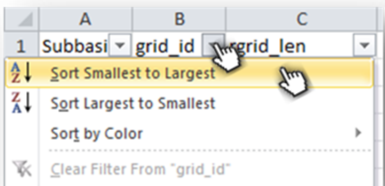


| | A | B | C |
|---|---|---|---|
| 1 | Subbasin | grid_id | rgrid_len |
| 2 | 49 | 2052 | 166.06600000000 |
| 3 | 49 | 1916 | 220.71100000000 |
| 4 | 49 | 1780 | 247.63500000000 |
| 5 | 49 | 1644 | 212.42600000000 |
| 6 | 49 | 1508 | 281.77700000000 |
| 7 | 49 | 1371 | 35.35530000000 |
| 8 | 25 | 1371 | 55.00000000000 |
| 9 | 25 | 1372 | 119.85300000000 |
| 10 | 17 | 1371 | 282.63500000000 |
| 11 | 17 | 1234 | 245.56300000000 |
| 12 | 17 | 1098 | 153.64000000000 |
| 13 | 9 | 2051 | 173.49200000000 |
| 14 | 9 | 2052 | 77.42640000000 |

- Use Filter and Sort the “grid_id” column in ascending order



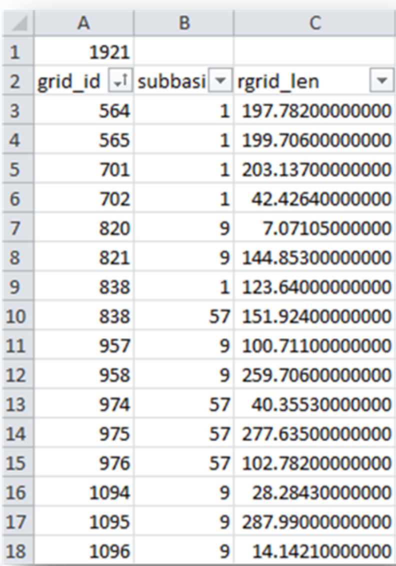




- Change the order of the columns and correct the column names

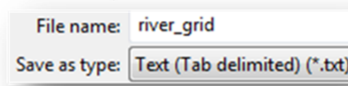
- Insert one row at the top of the spreadsheet and write the number of lines with information (starting on Line 3)

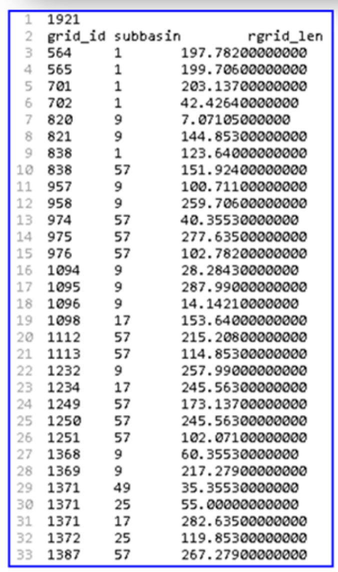
- Reduce the number of digits after decimal point if desired



| | A | B | C |
|---|---|---|---|
| 1 | 1921 | | |
| 2 | grid_id | subbasi | rgrid_len |
| 3 | 564 | 1 | 197.78200000000 |
| 4 | 565 | 1 | 199.70600000000 |
| 5 | 701 | 1 | 203.13700000000 |
| 6 | 702 | 1 | 42.42640000000 |
| 7 | 820 | 9 | 7.07105000000 |
| 8 | 821 | 9 | 144.85300000000 |
| 9 | 838 | 1 | 123.64000000000 |
| 10 | 838 | 57 | 151.92400000000 |
| 11 | 957 | 9 | 100.71100000000 |
| 12 | 958 | 9 | 259.70600000000 |
| 13 | 974 | 57 | 40.35530000000 |
| 14 | 975 | 57 | 277.63500000000 |
| 15 | 976 | 57 | 102.78200000000 |
| 16 | 1094 | 9 | 28.28430000000 |
| 17 | 1095 | 9 | 287.99000000000 |
| 18 | 1096 | 9 | 14.14210000000 |

- Save the spreadsheet as text file format



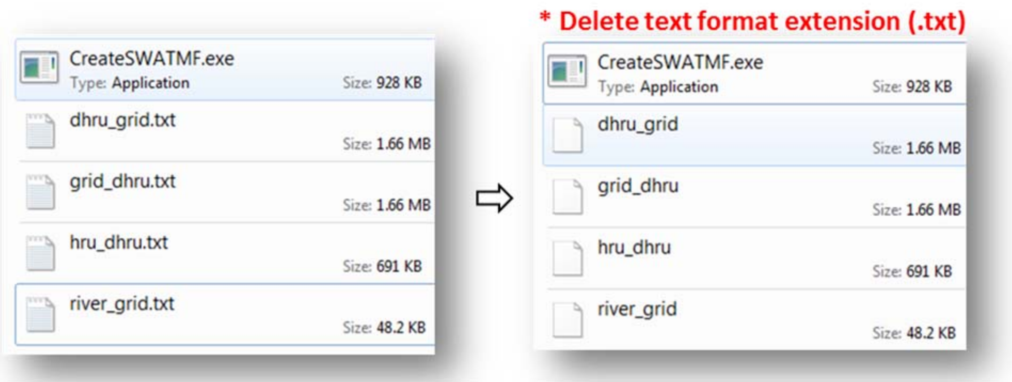



```
1921
grid_id subbasin        rgrid_len
564     1       197.78200000000
565     1       199.70600000000
701     1       203.13700000000
702     1       42.42640000000
820     9       7.07105000000
821     9       144.85300000000
838     1       123.64000000000
838     57      151.92400000000
957     9       100.71100000000
958     9       259.70600000000
974     57      40.35530000000
975     57      277.63500000000
976     57      102.78200000000
1094    9       28.28430000000
1095    9       287.99000000000
1096    9       14.14210000000
1098    17      153.64000000000
1112    57      215.20800000000
1113    57      114.85300000000
1232    9       257.99000000000
1234    17      245.56300000000
1249    57      173.13700000000
1250    57      245.56300000000
1251    57      102.07100000000
1368    9       60.35530000000
1369    9       217.27900000000
1371    49      35.35530000000
1371    25      55.00000000000
1371    17      282.63500000000
1372    25      119.85300000000
1387    57      267.27900000000
```

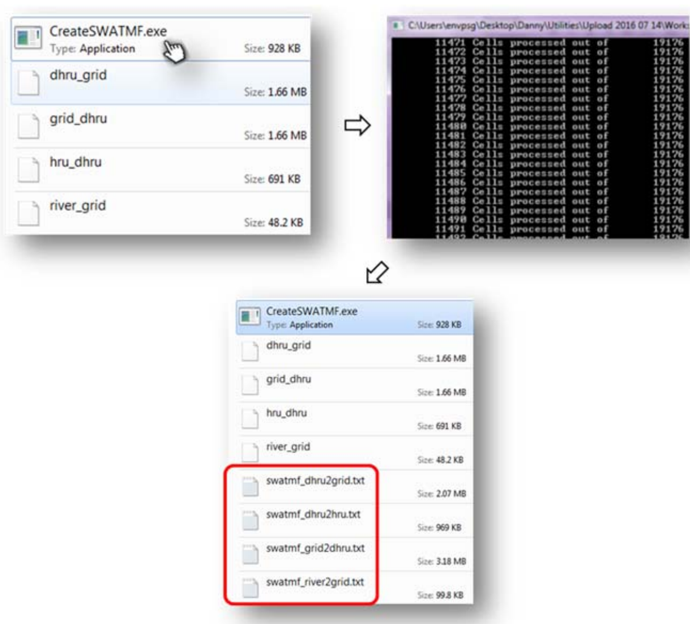
## 4.2 CREATE SWAT-MODFLOW LINKAGE FILES

Now that the four linkage tables (hru_dhru, dhru_grid, grid_dhru, river_grid) 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 **Files\3 Linking\2 Creating SWATMF files**, where the *CreateSWATMF.exe* FORTRAN program is located. 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 take approximately 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. This text file contains basic information for the SWAT-MODFLOW simulation. An example file is annotated below. The text written after the numbers are optional, but added here for explanation purposes.

```
1       SWAT-MODFLOW is activated flag (0 or 1): 1 if SWAT-MODFLOW is to be used
1       MODFLOW Pumping --> SWAT Irrigation flag (0 or 1): see Section 7.1
0       SWAT Auto-Irrigation --> MODFLOW Pumping  flag (0 or 1): see Section 7.1
1       MODFLOW Drains --> SWAT subbasin channels  flag (0 or 1): see Section 7.2
1       RT3D is active (N and P groundwater reactive transport) flag (0 or 1): see Section 8
1       Read in observation cells from "modflow.obs" flag (0 or 1): see Section 4.3.9
Optional output for SWAT-MODFLOW (0=no; 1=yes)
1       SWAT Deep Percolation (mm) (for each HRU)
1       MODFLOW Recharge (m3/day) (for each MODFLOW Cell)
1       SWAT Channel Depth (m) (for each SWAT Subbasin)                              flags (0 or 1)
1       MODFLOW River Stage (m) (for each MODFLOW River Cell)                        for output
1       Groundwater/Surface Water Exchange (m3/day) (for each MODFLOW River Cell)
1       Groundwater/Surface Water Exchange (m3/day) (for each SWAT Subbasin)
1       Print out average values for SWAT-MODFLOW and RT3D output variables flag (0 or 1) for monthly and annual
Write SWAT-MODFLOW output only on specified days                                     average output
7 number of output days for the 6 optional output variables
365
730
1095     List of output days. On these days, daily values for
1460     variables listed under "Optional output for SWAT-
1825     MODFLOW" will be written to output files.
3650
5475
Groundwater delay
0       0 = read in a single value for all HRUs; 1 = read in one value for each HRU Groundwater delay value
5       GW_DELAY : Groundwater delay [days]                                          (the values in the HRU
                                                                                     .gw files are not used)
```

## 4.3 Preparing basic MODFLOW Model Input Files

Groundwater modeling user interface software such as ModelMuse, GMS, VisualMODFLOW, or Groundwater Vistas are recommended to prepare MODFLOW models and their associated input files. MODFLOW package input files can also be prepared according to instructions available on the "Online Guide to MODFLOW-NWT" website: [https://water.usgs.gov/ogw/modflow-nwt/MODFLOW-NWT-Guide/](https://water.usgs.gov/ogw/modflow-nwt/MODFLOW-NWT-Guide/). This section describes only the packages that are required for SWAT-MODFLOW simulations, and their basic format. For the LRW example, files are provided in **Files\2 MODFLOW LRW\MODFLOW model**.

### 4.3.1 MODFLOW Name file

The MODFLOW name file lists all input and output files for a MODFLOW simulation. For stand-alone MODFLOW simulations, the user can provide any file name for the name file (e.g. modflow_LRW.nam). However, for SWAT-MODFLOW simulations, the code has been modified so that the file name modflow.mfn must be used. Below is an example of the contents of the name file, with red text provided only as description in the figure and is not in the actual file. The user decides the name for each input file. The boxed files are those required for SWAT-MODFLOW simulations. The output files are:

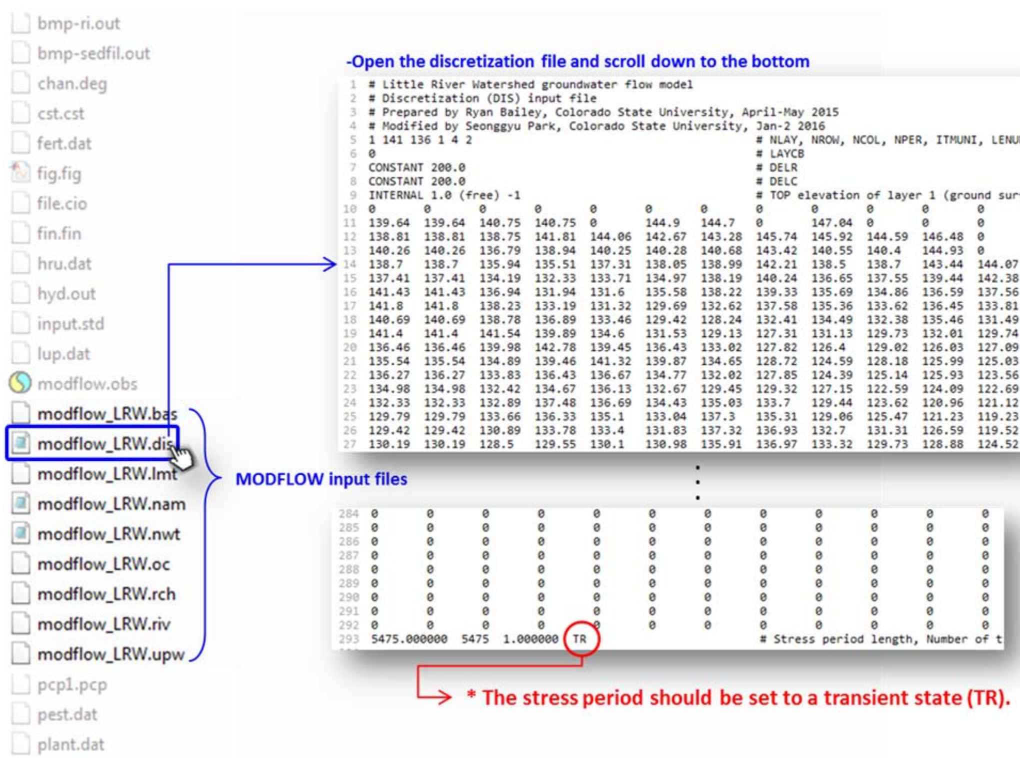
- modflow_LRW.out: main MODFLOW output, containing solver progress and water balance summaries
- modflow_LRW.hed: simulated groundwater head for each grid cell for time steps specified in the output control *.oc file (see Section 4.3.3)
- modflow_LRW.ccf: binary file containing flow rate and head data for each grid cell

```
# MODFLOW-NWT name file
# Output Files
LIST            5007    modflow_LRW.out
DATA            5030    modflow_LRW.hed
DATA(BINARY)    5040    modflow_LRW.ccf
# Global Input Files
DIS             5010    modflow_LRW.dis    Discretization (grid, timesteps)
# Flow Process Input Files
BAS6            5001    modflow_LRW.bas    Basic package (active cells, initial head)
UPW             5011    modflow_LRW.upw    Upstream Weighting package (aquifer properties)
RCH             5018    modflow_LRW.rch    Recharge package
RIV             5008    modflow_LRW.riv    River package
NWT             5013    modflow_LRW.nwt    Newton solver
OC              5022    modflow_LRW.oc     Output control
LMT6            5019    modflow_LRW.lmt    Linker file
EVT             5020    modflow_LRW.evt    Evapotranspiration package
DRN             5021    modflow_LRW.drn    Drain package
WEL             5023    modflow_LRW.wel    Well package (groundwater pumping)
```

The integers next to each package (e.g. 5018 for the Recharge package) are file index identifiers used by the MODFLOW code. These numbers are often below 100 for stand-alone MODFLOW simulations. However, as each input/output file in the SWAT-MODFLOW simulation must have a unique number, the MODFLOW input and output files are given numbers > 5000 so as not to coincide with numbers already provided to the numerous SWAT input files. **Therefore: always check the numbers in the modflow.mfn file to make sure they are above 5000.**

### 4.3.2 MODFLOW Discretization file

The Discretization file (e.g. modflow_LRW.dis for this example) contains all information for spatial (grid cell size and layering) and temporal (time steps, stress periods) discretization. Instructions for preparing the Discretization input file is found at https://water.usgs.gov/ogw/modflow-nwt/MODFLOW-NWT-Guide/. MODFLOW can be run in two settings: "steady-state" (SS) and "transient" (TR) (i.e. unsteady flow). When linked with SWAT, the "transient" option must be specified. This option is found at the bottom of the file, as shown in the diagram below. <u>If the setting is "SS", change to "TR"</u> (if this is not changed, then SWAT-MODFLOW will not run).




### 4.3.3 MODFLOW Output Control file

The output control input file (in this example it is named modflow_LRW.oc) contains instructions for MODFLOW to print groundwater head and water balance at specified time steps. The groundwater head will be written to the *.hed file specified in the modflow.mfn file (modflow_LRW.hed), and the water balance data will be written to the *.out file (modflow_LRW.out). Instructions for preparing the Output Control file is found at https://water.usgs.gov/ogw/modflow-nwt/MODFLOW-NWT-Guide/.

### 4.3.4 MODFLOW River Package file

The River package must be activated to enable groundwater-surface water exchange between MODFLOW grid cells and SWAT subbasin channels. Instructions for preparing the River package input file is found at [https://water.usgs.gov/ogw/modflow-nwt/MODFLOW-NWT-Guide/](https://water.usgs.gov/ogw/modflow-nwt/MODFLOW-NWT-Guide/). The first part of an example file (modflow_LRW.riv) is shown here, with red text for commentary. There is one row for each River cell. <u>Important</u>: the values of *Riverbed Conductance* and *Riverbed Elevation* listed in the file are used throughout the simulation. However, *River Stage* is provided by SWAT subbasin channels, and thus the values listed in the River package input file are over-written during the SWAT-MODFLOW simulation.

```
# Little River Watershed groundwater flow model
1633     0  Number of River Cells (maximum)
1633     0  Number of River Cells (current stress period)
```

| Cell Layer | Cell Row | Cell Column | River Stage [L] | Riverbed Conductance $[L^2/T]$ | Riverbed Elevation [L] |
|---|---|---|---|---|---|
| 1 | 5 | 20 | 126.3030 | 1786.6600 | 126.1400 |
| 1 | 5 | 21 | 126.6130 | 1804.0400 | 126.4500 |
| 1 | 6 | 21 | 125.2730 | 1835.0400 | 125.1100 |
| 1 | 6 | 22 | 127.9330 | 383.2590 | 127.7700 |
| 1 | 7 | 4 | 132.2580 | 98.9813 | 132.0400 |
| 1 | 7 | 5 | 131.9180 | 2027.6500 | 131.7000 |
| 1 | 7 | 22 | 125.0740 | 3560.2900 | 124.8700 |
| 1 | 8 | 5 | 131.6380 | 1409.7500 | 131.4200 |
| 1 | 8 | 6 | 130.0080 | 3635.3600 | 129.7900 |
| 1 | 8 | 22 | 127.1660 | 678.2110 | 126.9200 |
| 1 | 8 | 23 | 123.4660 | 4665.9300 | 123.2200 |
| 1 | 8 | 24 | 124.6260 | 1727.3500 | 124.3800 |

### 4.3.5 MODFLOW Recharge Package file

The Recharge package must be activated to enable recharge from SWAT HRUs to be mapped to the MODFLOW grid cells. Instructions for preparing the Recharge package input file is found at [https://water.usgs.gov/ogw/modflow-nwt/MODFLOW-NWT-Guide/](https://water.usgs.gov/ogw/modflow-nwt/MODFLOW-NWT-Guide/). In this example, the file is named modflow_LRW.rch. The basic file structure is:

```
# Little River Watershed groundwater flow model
3 40                                            # NRCHOP, IRCHCB
0 0
CONSTANT 0.00168                                # RECH (L/T)
```

The “CONSTANT” signifies the rate of 0.00168 m/day will be applied to each MODFLOW grid cell. <u>Important</u>: as MODFLOW receives recharge values from SWAT HRUs, the values provided in the Recharge package input file <u>are over-written and not used</u> during the SWAT-MODFLOW simulation. Thus, any values can be listed in the input file, and will not affect the SWAT-MODFLOW results.

### 4.3.6 MODFLOW EVT Package file

The Recharge package must be activated to enable ET from shallow groundwater. This ET is in addition to the ET from the soil profile as calculated for SWAT HRUs. Instructions for preparing the EVT package input file is found at https://water.usgs.gov/ogw/modflow-nwt/MODFLOW-NWT-Guide/. In this example, the file is named modflow_LRW.evt. The basic file structure is:

```
# EVT: Evapotranspiration package file created on 7/6/2018 by ModelMuse version 3.10.0.0.
       3      0 # DataSet 2: NEVTOP IEVTCB
       1      1      1     -1 # Data Set 5: INSURF INEVTR INEXDP INIEVT Stress period 1
CONSTANT 0.000                 # Data Set 6: SURF Ground surface elevation [L]
CONSTANT 0.000                 # Data Set 7: EVTR Potential ET rate [L/T]
CONSTANT 2.000                 # Data Set 9: EXDP Extinction depth [L], below which no ET occurs
```

Notice that the SURF and EVTR array values are set to 0.000. Within the SWAT-MODFLOW code, the SURF cell values (ground surface elevation) are given the elevation of the cells in the top layer, and the EVTR values are given the difference between potential ET and actual ET simulated by each SWAT HRU, with the HRU values mapped to the MODFLOW grid cells:

$$EVTR = ET_{potential} - ET_{actual}$$

This residual ET can be removed from the saturated zone of the aquifer, as long as the water table is above the extinction depth EXDP. The user can modify the value for EXDP. For this example, EXDP is set to 2.0 m below the ground surface, i.e. ET from groundwater cannot occur when the water table drops to below 2.0 m from the ground surface. If ET from shallow groundwater is not desired, then the user should set EXDP to 0.00.

### 4.3.7 MODFLOW Well Package file

The Well package can be activated to enable pumping from the aquifer. Instructions for preparing the Well package input file is found at https://water.usgs.gov/ogw/modflow-nwt/MODFLOW-NWT-Guide/. In this example, the file is named modflow_LRW.wel. The basic file structure is:

```
#Well package input file
8 0 AUX IFACE NAME  Number of Pumping Cells (maximum)
8 0                 Number of Pumping Cells (current stress period)
1       78      94      -1000
1       82      85      -1000
1       90      91      -1000
1       90      100     -1000
1       93      91      -1000
1       94      105     -1000
1       96      91      -1000
1       96      102     -1000
Cell    Cell    Cell    Pumping
Layer   Row     Column  Rate
                        [L³/T]
```

In this model, there are 8 pumping wells, located in eight different grid cells, each with a pumping rate of 1,000 $m^3$/day. Note that pumping rates are specified as negative values, since they signify water being removed from the groundwater system. Pumping rates can be linked with SWAT HRUs for groundwater irrigation, as discussed in Section 7.1.

### 4.3.8 MODFLOW Drain Package file

The Drain package can be activated to enable subsurface drainage from the aquifer. Instructions for preparing the Drain package input file is found at [https://water.usgs.gov/ogw/modflow-nwt/MODFLOW-NWT-Guide/](https://water.usgs.gov/ogw/modflow-nwt/MODFLOW-NWT-Guide/). In this example, the file is named modflow_LRW.drn. The file structure is very similar to that of the River package. The basic file structure is:

```
#Drain package input file
162      0 Number of Drain Cells (maximum)
162      0 Number of Drain Cells (current stress period)
1        34       15       134.27   100.00   0
1        36       19       133.34   100.00   0
1        37       19       130.56   100.00   0
1        34       15       134.27   100.00   0
1        35       15       131.34   100.00   0
1        36       13       133.35   100.00   0
1        36       14       128.83   100.00   0
1        36       15       129.07   100.00   0
1        37       13       130.03   100.00   0
1        37       14       126.85   100.00   0
Cell     Cell     Cell      Drain       Drain
Layer    Row      Column    Elevation   Conductance
                            [L]         [L²/T]
```

In this model, there are 162 drain cells, with the layer, row, column, drain elevation, and drain conductance value specified for each drain cell (only the first 13 cells are shown here). The volume of groundwater removed via each drain can be transferred to SWAT subbasin channels within SWAT-MODFLOW, as discussed in Section 7.2.

### 4.3.9 MODFLOW Observation Cell file

Daily groundwater head values can be output for selected MODFLOW grid cells, termed "observation cells". These values can then be plotted as a groundwater well hydrograph time series, and compared to groundwater level data from monitoring wells. The modflow.obs file lists these cells:

```
MODFLOW observation cells (number of cells, I,J,K for each cell)
15 Number of observation cells
19 2 1
15 8 1
49 15 1
75 11 1
93 31 1
39 35 1
29 44 1
85 48 1
95 61 1
56 64 1
132 93 1
114 103 1
137 113 1
135 125 1
139 132 1
Cell Cell  Cell
Row  Col   Layer
```

In this example, there are 15 cells designated as observation cells, with the row, column, and layer index listed for each cell. As it is not listed in the name file (modflow.mfn), the file must be named modflow.obs. To have SWAT-MODFLOW read this file, change the flag to "1" in the swatmf_link.txt file (see Section 4.3.1).

# 5. RUNNING A SWAT-MODFLOW SIMULATION

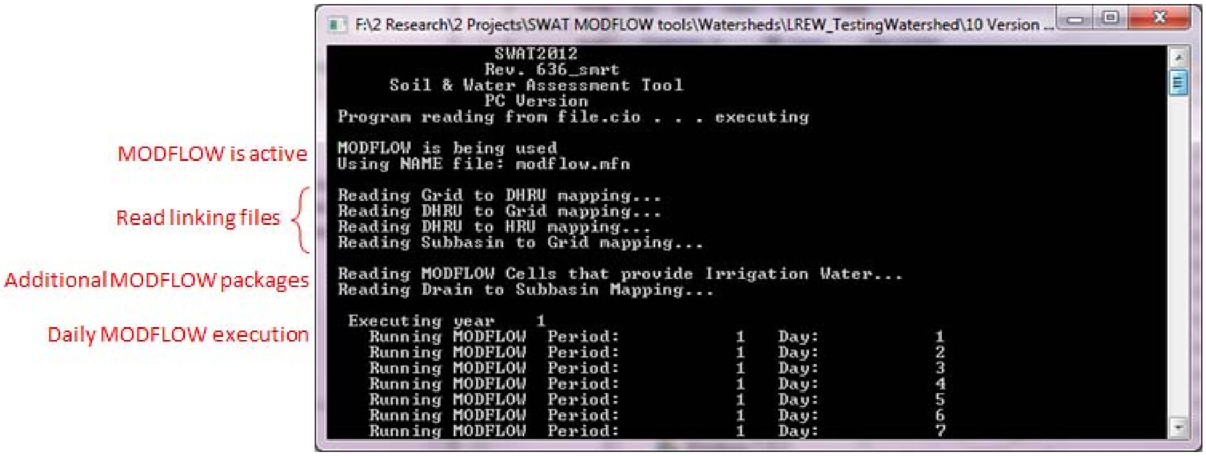
## 5.1 ASSEMBLING MODEL INPUT FILES

The SWAT-MODFLOW code requires all files to be placed in the same folder. The following files should be placed in the same folder (e.g. **Files\4 SWAT MODFLOW LRW**):

1. SWAT input files
2. MODFLOW input files
3. MODFLOW name file (modflow.mfn)
4. SWAT-MODFLOW linking file (swatmf_link.txt)
5. MODFLOW observation file (modflow.obs) (only if specified in swatmf_link.txt)
6. SWAT-MODFLOW Mapping files:
    a. swatmf _dhru2hru.txt
    b. swatmf _dhru2grid.txt
    c. swatmf _grid2dhru.txt
    d. swatmf _river2grid.txt
7. SWAT-MODFLOW executable (SWAT-MODFLOW3.exe)

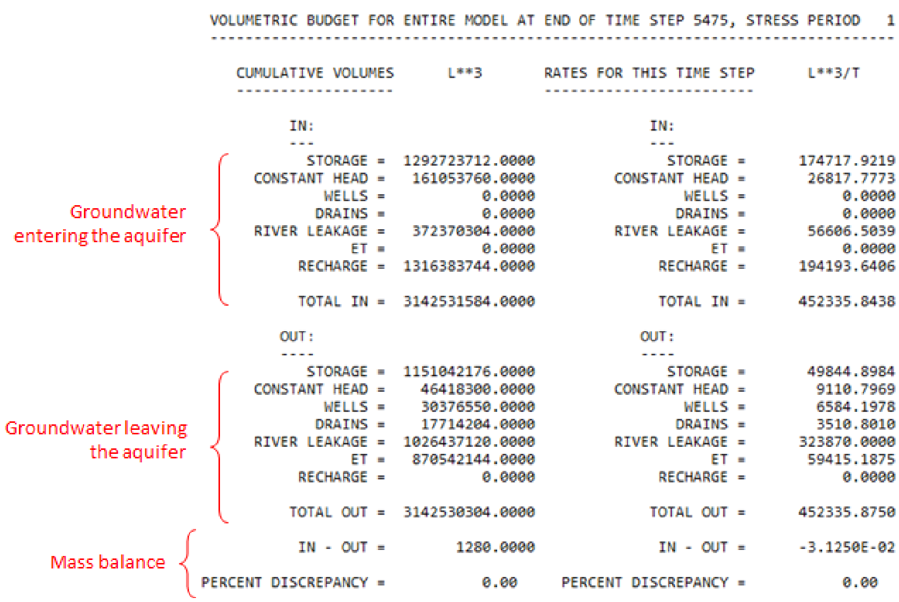
## 5.2 RUN SWAT-MODFLOW

When all files are in the same folder, double-click the SWAT-MODFLOW executable (SWAT-MODFLOW3.exe). This will start the model and bring up the console box, shown below. The box reports the progress of the model.



## 5.3 Checking Groundwater Mass Balance

For any MODFLOW simulation, the groundwater mass balance should be checked. This is performed by analyzing the water balance table in the main output file (modflow_LRW.out in this example). The following table shows the final water balance for the LRW SWAT-MODFLOW simulation. The table contains the groundwater inputs and outputs for each package used, followed by a mass percent discrepancy calculation (0.00 in this case). This percent discrepancy value should be less than 1.0; otherwise, the grid cell size and/or time steps should be decreased.




```
VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP 5475, STRESS PERIOD   1
------------------------------------------------------------------------------

   CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
   ------------------                 ------------------------

         IN:                                   IN:
         ---                                   ---
           STORAGE =  1292723712.0000            STORAGE =      174717.9219
     CONSTANT HEAD =   161053760.0000      CONSTANT HEAD =       26817.7773
             WELLS =           0.0000              WELLS =           0.0000
            DRAINS =           0.0000             DRAINS =           0.0000
     RIVER LEAKAGE =   372370304.0000      RIVER LEAKAGE =       56606.5039
                ET =           0.0000                 ET =           0.0000
          RECHARGE =  1316383744.0000           RECHARGE =      194193.6406

          TOTAL IN =  3142531584.0000           TOTAL IN =      452335.8438

        OUT:                                  OUT:
        ----                                  ----
           STORAGE =  1151042176.0000            STORAGE =       49844.8984
     CONSTANT HEAD =    46418300.0000      CONSTANT HEAD =        9110.7969
             WELLS =    30376550.0000              WELLS =        6584.1978
            DRAINS =    17714204.0000             DRAINS =        3510.8010
     RIVER LEAKAGE =  1026437120.0000      RIVER LEAKAGE =      323870.0000
                ET =   870542144.0000                 ET =       59415.1875
          RECHARGE =           0.0000           RECHARGE =           0.0000

         TOTAL OUT =  3142530304.0000          TOTAL OUT =      452335.8750

          IN - OUT =        1280.0000           IN - OUT =      -3.1250E-02

PERCENT DISCREPANCY =           0.00     PERCENT DISCREPANCY =         0.00
```

## 5.4 Troubleshooting

The SWAT-MODFLOW model can crash due to many reasons. Some of the most common reasons are:

- The linkage files are not created properly
- The swatmf_link.txt file is not created properly
- The MODFLOW name file is not "modflow.mfn"
- The MODFLOW input files are not created properly
- The irrigation and drainage flags are set to "1" in swatmf_link.txt, but there is no corresponding MODFLOW input file for the Well package or Drain package, respectively
- The MODFLOW solution does not converge

If the model crashes, there are 3 principal methods for determining the reason for the crash:

1. Open the main MODFLOW output file (modflow_LRW.out in this example) and scroll to the bottom of the file. The file will have text indicating the last procedure performed before crashing. For example, it may read "Reading Recharge file" on the last line, indicating that there is a problem with the Recharge input file. Or, the model may have attempted to solve the groundwater

equations for the first time step (or later time step), but the solver did not converge, leading to the crash. In this case, there will be a message stating “Stopped due to model convergence error”. To address model convergence, you may need to decrease the grid cell size or the time step size. You may also need to change solver settings (e.g. in the modflow_LRW.nwt file if you are using the Newton solver package: see [https://water.usgs.gov/ogw/modflow-nwt/MODFLOW-NWT-Guide/](https://water.usgs.gov/ogw/modflow-nwt/MODFLOW-NWT-Guide/).

2. Open the swatmf_log file. This file tracks the progress of SWAT-MODFLOW operations during model initialization. The following example file shows the progress during a successful model run. Using this file, you can see how far the model progressed before crashing, providing insight into what may have caused the crash. For example, if “MODFLOW files have been read” is the last line in the file, then likely there is a problem with the swatmf_grid2dhru.txt linking file.

```
Progress of SWAT-MODFLOW simulation

swatmf_link.txt:    file flags have been read
swatmf_link.txt:    MODFLOW is active
swatmf_link.txt:    Call interval is           1
swatmf_link.txt:    MODFLOW irrigation is active
swatmf_link.txt:    DRAIN cells are active
swatmf_link.txt:    Observation cell file needed
swatmf_link.txt:    output flags have been read
swatmf_link.txt:    output control has been read

swatmf_init: MODFLOW files have been read
swatmf_init: swatmf_grid2dhru.txt has been read
swatmf_init: swatmf_dhru2grid.txt has been read
swatmf_init: swatmf_dhru2hru.txt has been read
swatmf_init: swatmf_river2grid.txt has been read
swatmf_init: swatmf_irrigate.txt has been read
swatmf_init: swatmf_drain2sub.txt has been read
swatmf_init: initialization finished
```

3. Compile the SWAT-MODFLOW code provided in the general model download, and debug the model. *This is recommended only for modelers who have experience with computer programming and model compilation and debugging.*

# 6. VIEWING RESULTS

Besides the standard SWAT and MODFLOW output variables, SWAT-MODFLOW provides output related to water exchange rates between SWAT and MODFLOW. The basin-wide water balance is also modified to include SWAT-MODFLOW components.

## 6.1 BASIN-WIDE WATER BALANCE

### 6.1.1 Daily, Monthly, Annual Values

The following variables (all in units of mm) are added to the water balance data in the SWAT file output.std:

| | |
|---|---|
| GWQ: | Groundwater discharge to streams from MODFLOW River cells (as calculated by the River package) (this is the same variable name as in standard SWAT models, but now refers to exchange rates calculated by MODFLOW) |
| SWGW: | Seepage from streams to the aquifer (as calculated by the River package in MODFLOW) |
| RECH: | Recharge to the water table, as provided by SWAT HRUs. Over the length of the simulation the summation of recharge is equal to the summation of soil percolation (PERCOLATE), but the timing is different due to transport in the vadose zone as simulated by the groundwater delay parameter. |
| DRN: | Groundwater discharge to streams from MODFLOW Drain cells (as calculated by the Drain package) (this will have values only if the Drain package is active AND the MODFLOW Drain flag is set to "1" in swatmf_link.txt) |
| GW: | Total volume of groundwater in the aquifer (IMPORTANT: the method for calculating total groundwater volume is not exact, and thus this value is only an approximation of total groundwater volume. This value should not be used in groundwater balance calculations) |
| GWSTOR: | Change in groundwater storage |
| GWCON: | Groundwater entering the aquifer through constant head boundaries in the aquifer. Constant head cells are specified in the Basic package input file (modflow_LRW.bas in this example; for more information, see https://water.usgs.gov/ogw/modflow-nwt/MODFLOW-NWT-Guide/) |
| GWET: | Groundwater ET from the shallow water table, according to the extinction depth (EXDP) specified in the MODFLOW EVT package input file (modflow_LRW.evt in this example) |
| WATER YIELD: | Total water added to streams = SURQ + LATQ + TILE Q + GWQ – SWGW + DRN (new terms in blue) |

The following extract of output.std is for the first few days of the simulation, with the SWAT-MODFLOW variables boxed in blue:

```
    SWAT Mar 17 2015    VER 2012/Rev 636_smrt                                          0/ 0/   0     0: 0: 0

    General Input/Output section (file.cio):
    5/20/2015 12:00:00 AM ARCGIS-SWAT interface AV

         Number of years in run:   15
         Area of watershed:      331.882 km2
1
    SWAT Mar 17 2015    VER 2012/Rev 636_smrt

    General Input/Output section (file.cio):
    5/20/2015 12:00:00 AM ARCGIS-SWAT interface AV

Annual Summary for Watershed in year    1 of simulation

UNIT                                          PERCO             TILE
TIME      PREC    SURQ    LATQ    GWQ     SWGW    LATE    RECH    Q            DRN        SW      GW      GWSTOR  GWCON   GWET    ET      P
          (mm)    (mm)    (mm)    (mm)    (mm)    (mm)    (mm)    (mm)         (mm)       (mm)    (mm)    mm      mm      mm      (mm)    (
    1     0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00         0.01       117.63  919.15  0.02    0.04    0.04    0.75    1
    2    10.20    0.10    0.04    0.00    0.29    0.00    0.00    0.00         0.02       126.09  919.48  0.32    0.05    0.02    1.28    1
    3    12.70    0.28    0.13    0.00    0.29    0.00    0.00    0.00         0.02       137.66  919.81  0.33    0.06    0.00    0.22    0
    4     9.10    0.11    0.18    0.00    0.55    0.00    0.00    0.00         0.03       145.80  914.36  0.59    0.06    0.00    0.37    0
```

The water balance for the aquifer is:

$$GWSTOR = RECH + SWGW + GWCON - GWQ - DRN - GWET$$

<u>IMPORTANT</u>: a given MODFLOW model may include additional packages that are not included in this water balance. For example, the Lake package may be included, which simulates the water exchange rates between the aquifer and a lake. To include the lake/aquifer exchange in the groundwater balance, the values in the water balance tables in the main MODFLOW output file (modflow_LRW.out in this example) can be used. The following example performs the calculation for the Drain package, which is already included in output.std but is shown here for demonstration purposes. A similar calculation can be performed for any MODFLOW package included in the SWAT-MODFLOW simulation.

Using the following table, 3583 m$^3$ of groundwater exited the aquifer via drains (using the MODFLOW drain package) on day 5475. This volume can be converted to mm by dividing by the area of the watershed and multiplying by 1000. This could then be included in the groundwater balance equation above.

```
VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP 5475, STRESS PERIOD    1
------------------------------------------------------------------------------

  CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
  ------------------                 ------------------------

        IN:                                      IN:
        ---                                      ---
          STORAGE =  1051679744.0000                STORAGE =        743.4384
    CONSTANT HEAD =   160345648.0000          CONSTANT HEAD =      26618.9863
            WELLS =          0.0000                   WELLS =          0.0000
           DRAINS =          0.0000                  DRAINS =          0.0000
    RIVER LEAKAGE =   366869248.0000          RIVER LEAKAGE =      48423.6055
               ET =          0.0000                      ET =          0.0000
         RECHARGE =  1314643456.0000               RECHARGE =     859593.1875

         TOTAL IN =  2893538048.0000               TOTAL IN =     935379.2500

       OUT:                                     OUT:
       ----                                     ----
          STORAGE =   910766976.0000                STORAGE =     462464.3438
    CONSTANT HEAD =    46531332.0000          CONSTANT HEAD =       9117.3311
            WELLS =    30841630.0000                  WELLS =       6599.0752
           DRAINS =    18556544.0000                 DRAINS =       3583.2507
    RIVER LEAKAGE =  1081152768.0000          RIVER LEAKAGE =     398643.8750
               ET =   805687168.0000                     ET =      54971.3164
         RECHARGE =          0.0000                RECHARGE =          0.0000

        TOTAL OUT =  2893536256.0000              TOTAL OUT =     935379.1875

         IN - OUT =       1792.0000               IN - OUT =      6.2500E-02

PERCENT DISCREPANCY =           0.00    PERCENT DISCREPANCY =           0.00
```

<u>IMPORTANT</u>: The volumetric budget values in the MODFLOW output file account for all grid cells in the MODFLOW model domain. Therefore, if the MODFLOW domain is larger than the SWAT domain, a groundwater balance according to the preceding equation may not be achieved using only the values contained in the output.std file, as groundwater inputs/outputs may occur outside of the SWAT domain.

### 6.1.2 Average Annual Values

The tables of annual average values at the end of the output.std file include the SWAT-MODFLOW variables. The following table is from the example simulation. The SWAT-MODFLOW variables are boxed in blue, with the recharge provided to the water table from SWAT boxed in red.

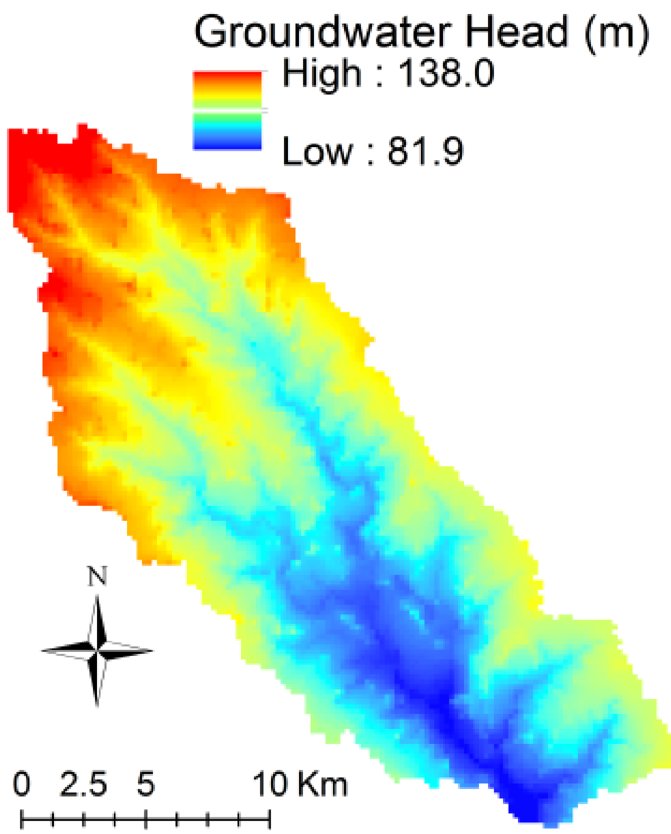
```
AVE ANNUAL BASIN VALUES

     PRECIP =    1140.5 MM
     SNOW FALL =     1.56 MM
     SNOW MELT =     1.56 MM
     SUBLIMATION =      0.00 MM
     SURFACE RUNOFF Q =    233.28 MM
     LATERAL SOIL Q =    23.42 MM
     TILE Q =      0.00 MM
     DRAIN Q (MODFLOW) =      3.73MM
     GROUNDWATER (SHAL AQ) Q =    164.21 MM
     GROUNDWATER (DEEP AQ) Q =      0.00 MM
     CHANGE IN GW STORAGE (MODFLOW) =    -28.04 MM
     CONSTANT HEAD Q (MODFLOW) =     22.88 MM
     RIVER SEEPAGE Q =     20.46 MM
     REVAP (SHAL AQ => SOIL/PLANTS) =     0.00 MM
     DEEP AQ RECHARGE =     0.00 MM
     TOTAL AQ RECHARGE =   252.22 MM
     TOTAL WATER YLD =   404.13 MM
     PERCOLATION OUT OF SOIL =   252.84 MM
     ET =     639.4 MM
     ET FROM GROUNDWATER (MODFLOW) =    161.90 MM
     PET =    1390.3MM
     TRANSMISSION LOSSES =      0.00 MM
     SEPTIC INFLOW =       0.00 MM
     TOTAL SEDIMENT LOADING =      5.800 T/HA
     TILE FROM IMPOUNDED WATER =      0.000 (MM)
     EVAPORATION FROM IMPOUNDED WATER =      0.000 (MM)
     SEEPAGE INTO SOIL FROM IMPOUNDED WATER =     0.000 (MM)
     OVERFLOW FROM IMPOUNDED WATER =    0.000 (MM)
```

## 6.2 MODFLOW Groundwater Head

### 6.2.1 Spatial Values

The groundwater head output file (modflow_LRW.hed in this example) 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 unconfined aquifers, the groundwater head is approximately equal to water table elevation for each grid cell, assuming there is minimal vertical flow in the aquifer. For each output time, there is a header line (time step, stress period), followed by the hydraulic head values written by row and column. Values for inactive cells (i.e. cells outside of the watershed boundary) are represented by a no-data value ("HNOFLO"), specified in the BASIC package input file (modflow_LRW.bas in this example, see line 148). Typically, this value is -999. Arrays for specific time steps can be imported into a GIS (e.g. ArcMap, QGIS) using ASCII → Raster conversion tools. An example plot is shown below, with the groundwater head spatial pattern similar to the topographic pattern. Maps of depth to water table can also be prepared by subtracting the groundwater head from the ground surface elevation, for each grid cell. Typically, the ground surface elevation is the elevation of the top grid layer, as found in the MODFLOW discretization file (modflow_LRW.dis in this example, see array beginning on line 10).



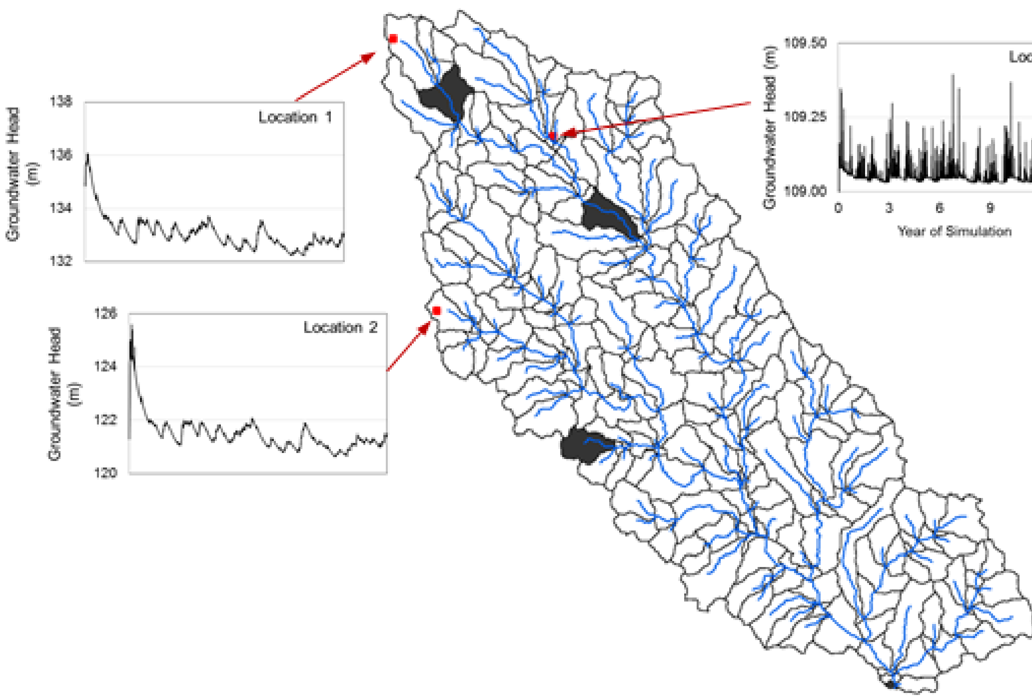
### 6.2.2 Groundwater Head for Observation Cells

As discussed in Section 4.3.9, groundwater head can be output for each MODFLOW time step for cells listed in the modflow.obs input file. Results are contained in swatmf_out_MF_obs. 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:

Head values for selected MODFLOW cells

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Day 1 | -999.0000 | 131.5338 | 122.7265 | -999.0000 | -999.0000 | 109.8433 | 115.0455 | 101.4626 | 94.6999 | 103.2069 | 98.1146 | 94.1717 | 92.8428 | 109.4227 | -999.0000 |
| Day 2 | -999.0000 | 131.3792 | 123.2763 | -999.0000 | -999.0000 | 109.9927 | 115.4626 | 101.7853 | 94.6485 | 103.1932 | 97.8517 | 94.2141 | 92.9063 | 109.3145 | -999.0000 |
| | -999.0000 | 131.2373 | 123.7187 | -999.0000 | -999.0000 | 110.1378 | 115.8123 | 102.0545 | 94.5964 | 103.1728 | 97.5973 | 94.2509 | 92.9687 | 109.2085 | -999.0000 |
| | -999.0000 | 131.1084 | 124.1981 | -999.0000 | -999.0000 | 110.2776 | 116.0990 | 102.2771 | 94.5439 | 103.1485 | 97.3593 | 94.2837 | 93.0285 | 109.1064 | -999.0000 |
| | -999.0000 | 130.9919 | 125.6239 | -999.0000 | -999.0000 | 110.4107 | 116.3291 | 102.4591 | 94.4914 | 103.1219 | 97.1400 | 94.3137 | 93.0838 | 109.0094 | -999.0000 |
| | -999.0000 | 130.8882 | 125.8830 | -999.0000 | -999.0000 | 110.5369 | 116.5118 | 102.6069 | 94.4394 | 103.0942 | 96.9389 | 94.3424 | 93.1341 | 108.9181 | -999.0000 |
| | -999.0000 | 130.7968 | 126.0039 | -999.0000 | -999.0000 | 110.6558 | 117.0509 | 102.7258 | 94.3882 | 103.0663 | 96.7549 | 94.3702 | 93.1790 | 108.8329 | -999.0000 |
| | -999.0000 | 130.7157 | 126.0276 | -999.0000 | -999.0000 | 110.7711 | 117.2811 | 102.8260 | 94.3384 | 103.0396 | 96.5862 | 94.3996 | 93.2209 | 108.7541 | -999.0000 |
| | -999.0000 | 130.6428 | 126.0122 | -999.0000 | -999.0000 | 110.8797 | 117.2899 | 102.9361 | 94.2898 | 103.0139 | 96.4315 | 94.4296 | 93.2584 | 108.6816 | -999.0000 |

As seen in the table, values listed in columns 1, 4, 5, and 15 are for cells that are inactive, and hence have the HNOFLO value of -999. Results can be used to create time series of hydraulic head for locations within the aquifer:



## 6.3 SWAT-MODFLOW Specific Output

The SWAT-MODFLOW simulation provides output for water exchange rates between the SWAT and MODFLOW systems. These are:

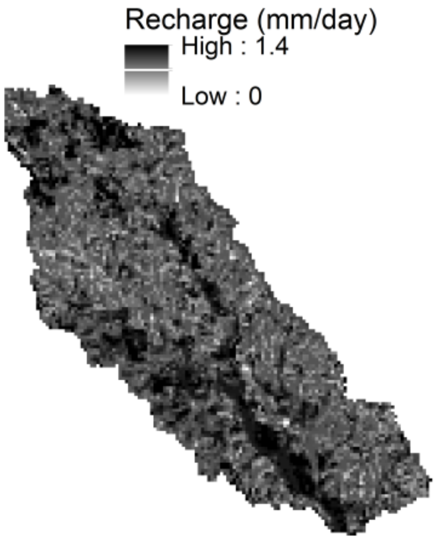
- Groundwater-surface water interaction
- Recharge
- River stage

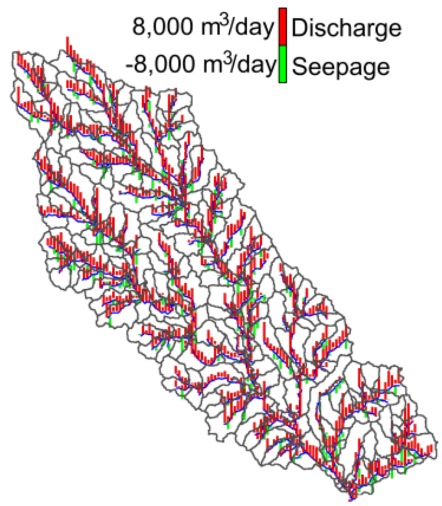
Output is provided for these three system variables from the perspective of both SWAT and MODFLOW (e.g. recharge is output for SWAT HRUs and for MODFLOW grid cells; if summed over the area of the watershed, these should be the same). Flags to turn on/off the writing of these files are specified in the swatmf_link.txt file. Output is provided on a daily basis for days specified in the swatmf_link.txt file (see Section 4.2). Monthly and yearly averaged values for each variable also are output, if the flag is turned on in the swatmf_link.txt file. Monthly and yearly average groundwater head values also are output. The following table summarizes the output files.

Note that the units for MODFLOW variables are in *L* (length) and *T* (time). SWAT-MODFLOW performs the appropriate unit conversions to convert between SWAT and MODFLOW variables, but output for MODFLOW always coincides with the length and time units specified in the MODFLOW discretization file (modflow_LRW.dis in this example; see line 5, variables ITMUNI and LENUNI).

| SWAT-MODFLOW Output File | | Units | Notes |
|---|---|---|---|
| **MODFLOW: Groundwater-Surface Water Exchange** | | | |
| | swatmf_out_MF_gwsw | $L^3/T$ | Flow rate of water exchanged between the aquifer and the river, for each MODFLOW River cell; Positive: River-->Aquifer; Negative: Aquifer-->River |
| | swatmf_out_MF_gwsw_monthly | $L^3/T$ | |
| | swatmf_out_MF_gwsw_yearly | $L^3/T$ | |
| **MODFLOW: Groundwater Head** | | | |
| | swatmf_out_MF_head_monthly | *L* | Groundwater head values for each MODFLOW grid cell |
| | swatmf_out_MF_head_yearly | *L* | |
| **MODFLOW: Recharge** | | | |
| | swatmf_out_MF_recharge | $L^3/T$ | Flow rate of water recharging the water table, for each MODFLOW grid cell |
| | swatmf_out_MF_recharge_monthly | $L^3/T$ | |
| | swatmf_out_MF_recharge_yearly | $L^3/T$ | |
| **MODFLOW: River Stage** | | | |
| | swatmf_out_MF_riverstage | *L* | River stage for each MODFLOW River cell |
| **SWAT: Groundwater-Surface Water Exchange** | | | |
| | swatmf_out_SWAT_gwsw | $m^3/day$ | Flow rate of water exchanged between the aquifer and the river, for each SWAT subbasin (for River, Drain, Stream packages) Positive: Aquifer-->River ; Negative: River-->Aquifer |
| | swatmf_out_SWAT_gwsw_monthly | $m^3/day$ | |
| | swatmf_out_SWAT_gwsw_yearly | $m^3/day$ | |
| **SWAT: Recharge** | | | |
| | swatmf_out_SWAT_recharge | *mm* | Depth of water recharing the water table, for each SWAT HRU; for swatmf_out_SWAT_recharge, the soil percolation depth is also listed. *groundwater delay is used to simulate timing of recharge* |
| | swatmf_out_SWAT_recharge_monthly | *mm* | |
| | swatmf_out_SWAT_recharge_yearly | *mm* | |
| **SWAT: River Stage** | | | |
| | swatmf_out_SWAT_channel | *m* | Channel depth for each SWAT subbasin channel |

Average annual HRU recharge and MODFLOW groundwater-surface water exchange rates are shown in the following figures for the LRW example:



# 7. Additional Hydrologic Linkages

Besides the basic link between SWAT and MODFLOW (i.e. recharge, groundwater-surface water interactions), several other features have been included to allow more flexibility in applying SWAT-MODFLOW to managed watersheds. These features include:

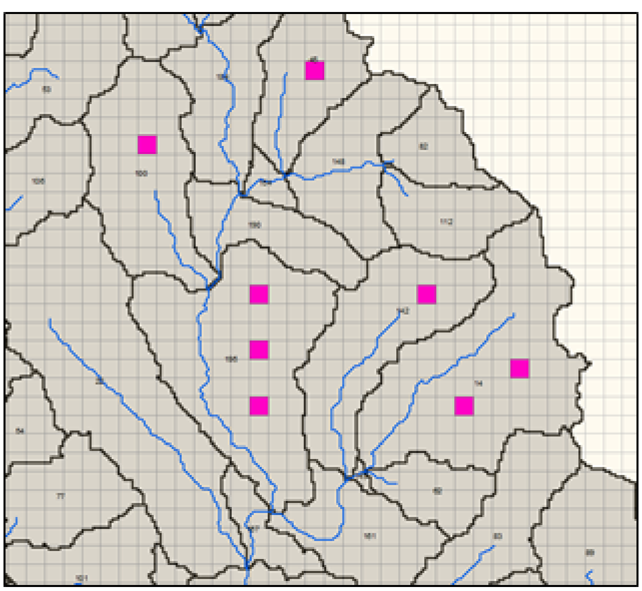
- Linking MODFLOW groundwater pumping to SWAT irrigation
- Linking MODFLOW subsurface drains to SWAT channel flow

## 7.1 Linking MODFLOW Pumping to SWAT Irrigation

Groundwater volumes can be transferred to land surface for irrigation via two methods: 1) groundwater pumping rates are dictated by MODFLOW; 2) groundwater pumping rates are dictated by SWAT auto-irrigation routines. These methods can be activated by setting the appropriate flags in swatmf_link.txt, as explained in 7.1.1 and 7.1.2. Only one of these options can be active for a simulation. Information for linking SWAT HRUs and MODFLOW pumping cells is contained in swatmf_irrigate.txt. However, as described in the next two sections, note that the content of the file is different based on which option is selected.

### 7.1.1 Pumping Rate Dictated by MODFLOW

The first method determines applied irrigation amounts for SWAT HRUs using the pumping rates specified in MODFLOW's WELL package. As an example, the following map shows a section of the Little River Watershed with 8 MODFLOW grid cells selected for groundwater pumping. The text for the WELL package input file also is shown, listing the layer, row, column, and pumping rate (-1000 $m^3$/day → negative signifies extraction from the aquifer) for each of the 8 pumping cells.

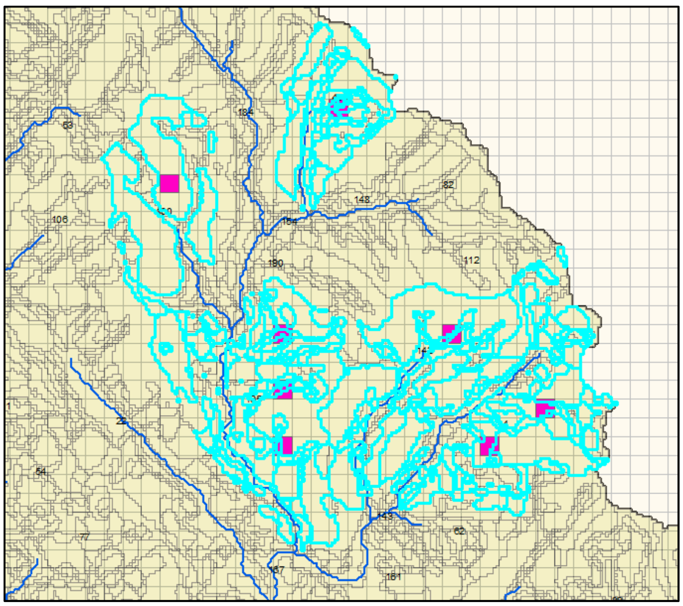


WELL package input file:

```
#Well package input file
8 0 AUX IFACE NAME
8 0
1       78      94      -1000
1       82      85      -1000
1       90      91      -1000
1       90      100     -1000
1       93      91      -1000
1       94      105     -1000
1       96      91      -1000
1       96      102     -1000
```

Groundwater removed from the selected MODFLOW grid cells is then transferred to selected HRUs. For example, the highlighted HRUs in the following map receive water from the 8 groundwater pumping cells. For each day during which pumping occurs, the following process is used to convert pumped groundwater volumes to irrigation depths (mm) for each WELL pumping cell:

1. Calculate volume of pumped groundwater ($m^3$)
2. Determine subbasin that receives irrigation water
3. Determine the set of HRUs within the specified subbasin that receive the irrigation water
4. Use the spatial areas of the receiving HRUs to convert the pumped groundwater volume ($m^3$) to an irrigation depth (mm)
5. Apply the irrigation depth (mm) on the following day



The information required for linkage MODFLOW pumping cells to receiving SWAT HRUs is contained in the input file swatmf_irrigate.txt. An example swatmf_irrigate.txt is provided with the Little River Watershed example (**Files\4 SWAT MODFLOW LRW\Scenarios\MODFLOW pumping irrigation**). The first section of the file lists the number of MODFLOW grid cells that provide irrigation water, followed by the *conveyance efficiency* and the *runoff ratio* for each subbasin. The conveyance efficiency value specified the fraction of pumped groundwater that reaches the irrigated field. A value of "1" indicates that all the groundwater reaches the field, whereas a value < 1 indicates that a portion of the groundwater is lost, e.g. due to evaporation as the water is transported along an open conduit, or seeped from an earthen canal.

```
This file contains a listing of MODFLOW grid cells, and their associated SWAT sub-basins
8                                                                Number of grid cells that provide irrigation water
Conveyance efficiency, Runoff Ratio for each sub-basin
1       0.05
1       0.05
1       0.05
1       0.05
1       0.05
1       0.05
1       0.05
```

The next section of the file lists the subbasin and HRU associated with each MODFLOW pumping cell:

```
1       0.05
1       0.05
Sub     Row     Col     HRU_ID
45      78      94      1193
100     82      85      2750
195     90      91      5136
142     90      100     3947
195     93      91      5137
14      94      105     362
195     96      91      5136
14      96      102     359
```

Notice that the row and column number for each of the pumping cells match the numbers in the WELL package input file shown previously in this section.

The last section of the file lists the number of HRUs that receive irrigation water, and the HRU ID and associated subbasin for each of these HRUs. This list is provided so

```
HRUs that receive irrigation water (Subbasin, HRU ID)
40   Number of HRUs that receive irrigation water
45      1193
45      1196
45      1198
45      1199
45      1212
45      1210
45      1211
100     2750
195     5136
195     5137     List of subbasin, HRU ID
195     5139
195     5141
195     5157
195     5159
195     5166
142     3947
142     3949
142     3967
195     5137
195     5148
```

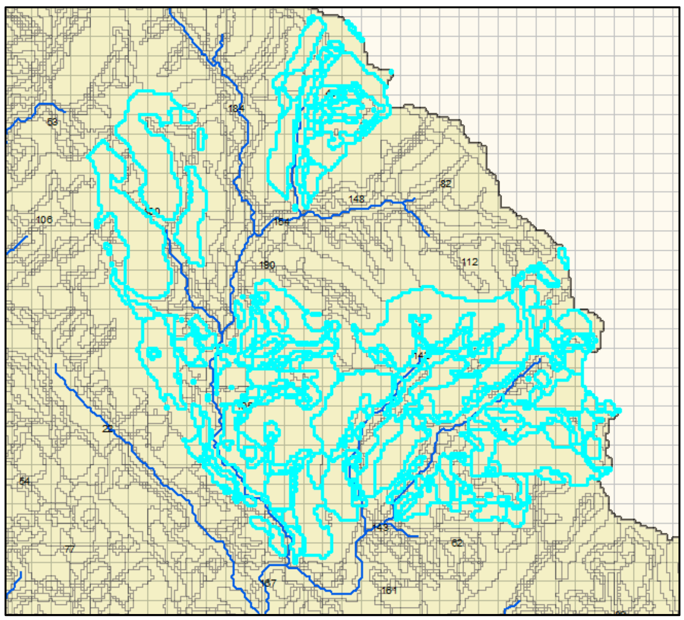
To active this option in SWAT-MODFLOW, set the appropriate flag in swatmf_link.txt:

```
1       SWAT-MODFLOW is activated
1       MODFLOW Pumping --> SWAT Irrigation
0       SWAT Auto-Irrigation --> MODFLOW Pumping
1       MODFLOW Drains --> SWAT subbasin channels
1       RT3D is active (N and P groundwater reactive transport)
1       Read in observation cells from "modflow.obs"
Optional output for SWAT-MODFLOW (0=no; 1=yes)
1       SWAT Deep Percolation (mm) (for each HRU)
1       MODFLOW Recharge (m3/day) (for each MODFLOW Cell)
```

Files required to run this option are available in **Files\4 SWAT MODFLOW LRW\Scenarios\MODFLOW pumping irrigation**. These files consist of the modified name file modfow.mfn, the WELL package file modflow_LRW.wel, swatmf_irrigate.txt, and the modified swatmf_link.txt file. These should be copied into the folder that contains all SWAT-MODFLOW files.

### 7.1.2 Pumping Rate Dictated by SWAT

The second method determines pumping rates for MODFLOW using the applied irrigation depths from SWAT's auto-irrigation routines. As an example, the following map shows a section of the Little River Watershed with HRUs that are set to receive irrigation using SWAT's auto-irrigation routines.



For each day during which auto-irrigation occurs, the following process is used to convert HRU irrigation depths (mm) to pumped groundwater volumes for MODFLOW WELL package pumping cell:

1. Irrigation depth (mm) for an HRU is specified using auto-irrigation routine
2. Convert the irrigation depth (mm) to volume ($m^3$) using the spatial area of the HRU
3. Find the MODFLOW cell that will provide the groundwater to the HRU
4. Check the available volume of groundwater in the MODFLOW cell; if the irrigation volume is greater than the available groundwater, then take the remainder and re-calculate the irrigation depth; otherwise, extract the full amount. The extracted volume becomes the pumping rates ($m^3$/day)
5. For each HRU, add a pumping cell to the MODFLOW WELL package with the calculated pumping rate ($m^3$/day)
6. MODFLOW uses the new set of pumping rates in its calculations for that day

The information required for linkage MODFLOW pumping cells to receiving SWAT HRUs is contained in the input file swatmf_irrigate.txt. An example swatmf_irrigate.txt is provided with the Little River Watershed example (**Files\4 SWAT MODFLOW LRW\Scenarios\MODFLOW SWAT autoirrigation**). The file contains only the list of HRUs that receive irrigation water, with the HRU subbasin # and the row, column, and layer of the MODFLOW grid cell from which groundwater will be extracted for irrigation:

```
Irrigation Pumping File for SWAT-MODFLOW
40 Number of HRUs that receive irrigation water
Sub     Row     Column  Lay     HRU_ID
45      78      94      1       1193
45      78      94      1       1196
45      78      94      1       1198
45      78      94      1       1199
45      78      94      1       1212
45      78      94      1       1210
45      78      94      1       1211
100     82      85      1       2750
195     90      91      1       5136
195     90      91      1       5137
195     90      91      1       5139
195     90      91      1       5141
195     90      91      1       5157
195     90      91      1       5159
195     90      91      1       5166
142     90      100     1       3947
142     90      100     1       3949
```

Indices for the MODFLOW grid cell that provides pumped groundwater to HRU 1193 for irrigation.

To active this option in SWAT-MODFLOW, set the appropriate flag in swatmf_link.txt:

```
1       SWAT-MODFLOW is activated
1       MODFLOW Pumping --> SWAT Irrigation
0       SWAT Auto-Irrigation --> MODFLOW Pumping
1       MODFLOW Drains --> SWAT subbasin channels
1       RT3D is active (N and P groundwater reactive transport)
1       Read in observation cells from "modflow.obs"
Optional output for SWAT-MODFLOW (0=no; 1=yes)
1       SWAT Deep Percolation (mm) (for each HRU)
```

<u>IMPORTANT</u>: The WELL package must be active for this option to be implemented. See Sections 4.3.7 and 4.3.1 for details on preparing a WELL package input file and listing the input file in the modflow.mfn file, respectively. The WELL package can contain pumping cells that are not associated with SWAT HRU irrigation.

<u>IMPORTANT</u>: The maximum number of pumping cells is listed on the first line in the WELL package input file (see Section 4.3.7). This number is used to dimension arrays within the MODFLOW code. As the option described in this section adds pumping cells to the WELL package, this number must be high enough to accommodate the added cells.

For example, if there are no initial WELL wells, than the file will be:

```
#Well package input file
8 0 AUX IFACE NAME
0 0

```

where the “8” indicates that there will be 8 pumping cells added to the WELL package due to linkage with SWAT HRUs for groundwater pumping.

Files required to run this option are available in **Files\4 SWAT MODFLOW LRW\Scenarios\MODFLOW SWAT autoirrigation**. These files consist of the modified name file modfow.mfn, the WELL package file modflow_LRW.wel, swatmf_irrigate.txt, and the modified swatmf_link.txt file. These should be copied into the folder that contains all SWAT-MODFLOW files.

IMPORTANT: The code for this option has not been tested extensively. Please contact the SWAT-MODFLOW authors if you plan to use this option.

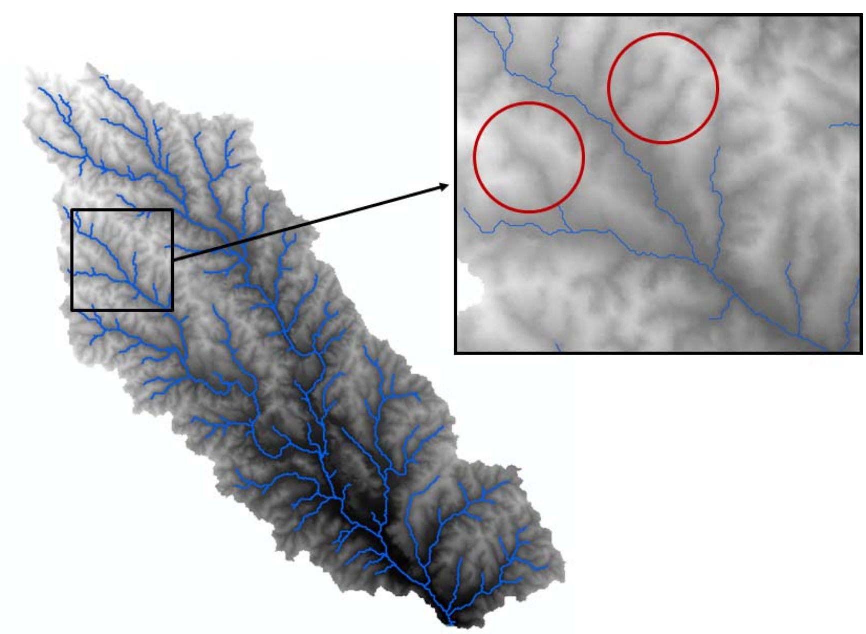
## 7.2 Linking MODFLOW Drains to SWAT Channels

### 7.2.1 Background

The MODFLOW DRAIN package simulates the removal of groundwater from the aquifer below a specified elevation. There are two main uses of the DRAIN package for SWAT-MODFLOW:

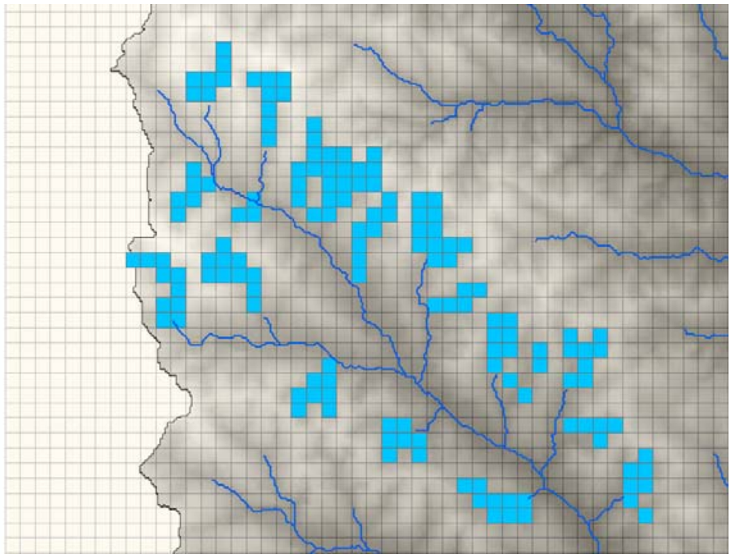
1. Removal of groundwater via subsurface drains. Conversely, this can be simulated using the SWAT tile drain equations.
2. Removal of groundwater from drainage areas in the watershed that are not included in SWAT’s subbasin channel network. For example, the following map shows the topography and the SWAT channel network of the Little River Watershed. The circled areas show drainages in the landscape that are not included in SWAT’s channel network.

For both options, the groundwater removed from the aquifer via the MODFLOW DRAIN cells must be routed to the SWAT subbasin to achieve a watershed water balance. The next section describes how this is accomplished in SWAT-MODFLOW.



### 7.2.2 Linking MODFLOW DRAIN cells to SWAT Subbasin Channels

Using the boxed area in the previous map as an example, the following map shows MODFLOW cells that are selected to be DRAIN cells (162 cells in total).



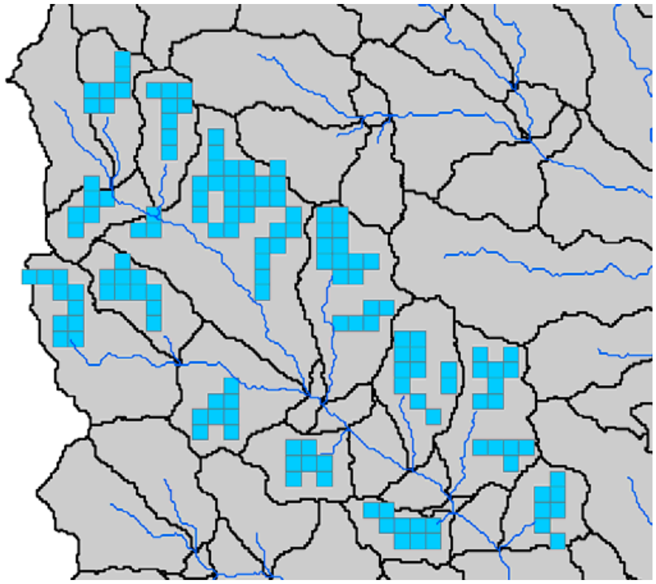
To simulate drainage from these grid cells, the MODLFOW DRAIN package must be activated, and an input file must be prepared (modflow_LRW.drn in this example; see **Files\4 SWAT MODFLOW LRW\Scenarios\MODFLOW Drains**). See Section 4.3.8 for details on creating the file. To active the package, the file name must be included in modflow.mfn (see Section 4.3.1).

For each day of the simulation, the volume of groundwater removed from each DRAIN cell is added to the streamflow in a subbasin channel. Therefore, the subbasin # must be specified for each DRAIN cell. This is contained in the input file swatmf_drain2sub.txt (see **Files\4 SWAT MODFLOW LRW\Scenarios\MODFLOW Drains** for the LRW example):

```
162   Number of MODFLOW DRAIN cells the contribute water to SWAT subbasins
Row     Column  Subbasin
34      15      85
36      19      97
37      19      97
34      15      19
35      15      19
36      13      19
36      14      19
36      15      19
37      13      19
37      14      19
36      17      43
36      18      43
```

List of 162 cells, with associated subbasin

The following map shows the DRAIN cells and the SWAT subbasins. These two shapefiles are intersected to provide the list of DRAIN cells within each subbasin, to populate swatmf_drain2sub.txt.



To active this option in SWAT-MODFLOW, set the appropriate flag in swatmf_link.txt:

```
1       SWAT-MODFLOW is activated
1       MODFLOW Pumping --> SWAT Irrigation
0       SWAT Auto-Irrigation --> MODFLOW Pumping
1       MODFLOW Drains --> SWAT subbasin channels
1       RT3D is active (N and P groundwater reactive transport)
1       Read in observation cells from "modflow.obs"
Optional output for SWAT-MODFLOW (0=no; 1=yes)
1       SWAT Deep Percolation (mm) (for each HRU)
1       MODFLOW Recharge (m3/day) (for each MODFLOW Cell)
```

Files required to run this option are available in **Files\4 SWAT MODFLOW LRW\Scenarios\MODFLOW Drains**. These files consist of the modified name file modfow.mfn, the DRAIN package file modflow_LRW.drn, swatmf_drain2sub.txt, and the modified swatmf_link.txt file. These should be copied into the folder that contains all SWAT-MODFLOW files.

# 8. Simulating N and P Groundwater Transport using RT3D

## 8.1 Introduction to SWAT-MODFLOW-RT3D

SWAT-MODFLOW can simulate the reactive transport of nitrate ($NO_3$) and phosphorus (P) in the aquifer system using the groundwater reactive transport simulator RT3D (Reactive Transport in 3 Dimensions) (Clement, 1997; https://bioprocess.pnnl.gov/) to provide a comprehensive watershed water quality reactive transport model. RT3D solves the mass conservative advection-dispersion-reaction (ADR) equation for concentration of solutes in a multi-dimensional groundwater system. RT3D uses groundwater flow rates and source/sink flow rates from MODFLOW simulations, with solute concentration calculated at each grid cell. For an application of SWAT-MODFLOW-RT3D for $NO_3$, please see Wei et al. (2018). First-order denitrification is included for $NO_3$. Linear sorption is included for P. For $NO_3$ and P, the ADR equations are:

$$\text{NO}_3\text{:}\quad \frac{\partial C_{NO_3}}{\partial t} = \overbrace{-\frac{\partial}{\partial x_i}\left(v_i C_{NO_3}\right)}^{\text{Advection}} + \overbrace{\frac{\partial}{\partial x_i}\left(D_{ij}\frac{\partial C_{NO_3}}{\partial x_j}\right)}^{\text{Dispersion}} + \overbrace{\frac{q_s}{\phi}C_{s_{NO_3}}}^{\text{Source/Sink}} \overbrace{-k_{NO_3}C_{NO_3}\left(\frac{C_{NO_3}}{K_{NO_3}+C_{NO_3}}\right)}^{\text{Denitrification}}$$

$$\text{P:}\quad \frac{\partial C_P}{\partial t}\underbrace{R_P}_{\uparrow\ \text{Sorption}} = \overbrace{-\frac{\partial}{\partial x_i}\left(v_i C_P\right)}^{\text{Advection}} + \overbrace{\frac{\partial}{\partial x_i}\left(D_{ij}\frac{\partial C_P}{\partial x_j}\right)}^{\text{Dispersion}} + \overbrace{\frac{q_s}{\phi}C_{s_P}}^{\text{Source/Sink}}$$

where $C$ is solute concentration [M/L$^3$]; $D_{ij}$ is the hydrodynamic dispersion coefficient [$L^2/T$]; $v$ is groundwater velocity [$L/T$], provided by MODFLOW; $\phi$ is porosity; $q_s$ is the volumetric flux of water representing sources and sinks of the species (e.g. pumping, recharge); $C_s$ is the concentration of the source or sink water; k is the first-order rate constant for denitrification [1/T]; $K_{NO_3}$ is the Monod half-saturation constant [M/L$^3$] for $NO_3$; and $R$ is the retardation coefficient representing sorption of phosphorus. $NO_3$ does not sorb within soil and groundwater systems, and therefore the $R$ is omitted. These two ADR equations are solved for each grid cell for each time step within the simulation, to provide cell-by-cell $NO_3$ and P groundwater concentrations.

## 8.2 Integration of RT3D into SWAT-MODFLOW

Within the SWAT-MODFLOW modeling code, RT3D is call as a subroutine within the MODFLOW subroutine. The basic process for implementing RT3D into the watershed water quality simulation scheme is as follows:

<u>For each day of the simulation</u>:

1. For each HRU: $NO_3$ and P mass (kg/ha) in recharge water is calculated using the mass of $NO_3$ and P leached from the soil profile and the HRU groundwater delay value (the same groundwater delay value used to calculate recharge)
2. For each HRU: $NO_3$ and P mass (kg/ha) in recharge water is converted to concentration (mg/L) using the area of the HRU and the volume of recharge water
3. The HRU $NO_3$ and P recharge concentration values are mapped to the RT3D grid cells (similar to recharge values mapped to the MODFLOW grid cells)
4. RT3D is called by MODFLOW to calculate the groundwater concentration of $NO_3$ and P in each grid cell
5. Groundwater mass loadings of $NO_3$ and P are added to the $NO_3$ and P mass in SWAT subbasin channels. This is performed by multiplying the cell groundwater solute concentration by the MODFLOW-simulated groundwater discharge flow rates. If channel water seeps into the aquifer, then the mass loading from the channel to the aquifer is calculated and removed from the $NO_3$ and P mass in the channels. *The exchange of $NO_3$ and P mass between the aquifer and the subbasin channels are performed for both the RIVER package cells and the DRAIN package cells.*

## 8.3 Preparing RT3D Input Files

The RT3D code has been changed to simplify input file preparation. RT3D uses the following packages, each with an input file:

| | |
|---|---|
| • Basic Transport package | Spatial / temporal discretization (i.e. grid, time steps) |
| • Advection package | Solute moves with groundwater flow |
| • Dispersion package | Solute mass is dispersed during transport |
| • Source-Sink Mixing package | Solute concentration in groundwater sources/sinks |
| • Reaction package | Chemical reactions (sorption, first-order kinetics) |
| • GCG package | Implicit solver |

Example files for the LRW model are contained in **Files\5 SWAT MODFLOW RT3D LRW**. The input files are listed in the name file rt3d_filenames:

```
'rt3d.btn'              INBTN=1         Basic Transport Package
'rt3d.adv'              INADV=2         Advection Package
'rt3d.dsp'              INDSP=3         Dispersion Package
'rt3d.ssm'              INSSM=4         Source/Sink Mixing Package
'rt3d.rct'              INRCT=5         Reaction Package
'rt3d.gcg'              INGCG=6         Implicit Solver Package
'rt3d.restart'          OUTRES=10       Restart File
```

Similar to the MODFLOW name file modflow.mfn, the files can be called any name, as long as the name of the file matches that listed in rt3d_filenames.

### 8.3.1 Basic Transport (BTN) Package file

The BTN input file (rt3d.btn in this example) contains information about the solutes, the grid cells, and the transport time step. Much of the input data should stay the same for any simulation. The red text in the following figures references input parameters and values that can be modified by the user:

```
'PACKAGES USED: ADV,DSP,SSM,RCT,GCG,AGR,VST,IGR,--- --------------------------'
T T T T T T F F F F F
'NCOMP, MCOMP ----------------------------------------------------------------'
2 2
'TYPE OF WRITING FOR OUTPUT FILES (0=ASCII/1=BINARY/2=BOTH) ------------------'
0
'SPECIES (MOBILE/IMMOBILE) ---------------------------------------------------'
'NO3' 1 1
'P' 1 1
'd'  'm'  'g'
'POROSITY FOR EACH LAYER -----------------------------------------------------'
0       0       0       0       0       0       0       0       0       0       0       0       0
0       0.2     0.2     0.2     0       0.2     0.2     0       0.2     0       0       0       0
0       0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0       0
0       0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0       0
0       0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2
0       0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2
0       0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2
0       0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2
0       0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2
0       0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2
0       0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2
0       0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2
0       0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2
0       0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2
0       0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2
0       0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2     0.2
```

Porosity for each active grid cell;

Repeat array for each layer in the grid

.

.

.

```
'ICBUND ARRAY ----------------------------------------------------------------'
0       0       0       0       0       0       0       0       0       0       0       0       0
0       1       1       1       0       1       1       0       1       0       0       0       0
0       1       1       1       1       1       1       1       1       1       1       0       0
0       1       1       1       1       1       1       1       1       1       1       0       0
0       1       1       1       1       1       1       1       1       1       1       1       1
0       1       1       1       1       1       1       1       1       1       1       1       1
0       1       1       1       1       1       1       1       1       1       1       1       1
0       1       1       1       1       1       1       1       1       1       1       1       1
0       1       1       1       1       1       1       1       1       1       1       1       1
0       1       1       1       1       1       1       1       1       1       1       1       1
0       1       1       1       1       1       1       1       1       1       1       1       1
0       1       1       1       1       1       1       1       1       1       1       1       1
0       1       1       1       1       1       1       1       1       1       1       1       1
0       1       1       1       1       1       1       1       1       1       1       1       1
0       1       1       1       1       1       1       1       1       1       1       1       1
0       1       1       1       1       1       1       1       1       1       1       1       1
```

Active/inactive flag for each grid cell (same array as in modflow_LRW.bas)

Only write once; if other layers, values are copied to other layers

.

.

.

```
0       0       0       0       0       0       0       0       0       0       0       0       0       0       0
'INITIAL CONCENTRATIONS: EACH SPECIES ---------------------------------------'
0 0.00   CNO3 Initial concentration of NO3 in each grid cell in the layer (repeat line for the number of layers in the grid
0 0.00   CP   Initial concentration of P in each grid cell in the layer (repeat line for the number of layers in the grid
'VALUE INDICATING INACTIVE CELL CONCENTRATION --------------------------------'
 -999.0000
'IFMTCN(print), IFMTNP(particle), IFMTRF(R), IFMTDP(D), SAVUCN(binary) --------'
6       0       0       0       F
'NUMBER OF OUTPUT TIMES -----------------------------------------------------'
15 Number of times for which all cell concentration values will be written to swatmf_out_RT_CONC files
'OUTPUT TIMES   ------------------------------------------------------------'
365     730     1095    1460    1825    2190    2555    2920    3285    3650    4015    4380    4745    5110    5475 List of output times (days)
'OBSERVATION    CELLS:  I,J,K   -------------------------------------------'
2 1 Number of observation cells
100 50 1    Cells (row, column, layer) for which daily concentration of
50 50 1     NO3 and P will be written to swatmf_out_RT_OBS files
'OUTPUT MASS    BUDGET  FILES   ---------------------------------------------------'
F
```

### 8.3.2 Advection (ADV) Package file

The ADV input file (rt3d.adv in this example) specifies the method for simulating advection. There is nothing to change in this file.

```
         0 1.0000000         1
```

### 8.3.3 Dispersion (DSP) Package file

The DSP input file (rt3d.dsp in this example) specifies the values of aquifer dispersivity.

```
'LONGITUDINAL DISPERSIVITY ---------------------------------------------------'
        0 2.000000 Constant value assigned to each grid cell in the layer (repeat line for the number of layers in the grid
'RATIO OF HORIZ. TRANSVERSE TO LONG. DISP. ----------------------------------'
        0 0.1000000 Constant value assigned to each cell in the model
'RATIO OF VERTIC. TRANSVERSE TO LONG. DISP. ---------------------------------'
        0 0.1000000 Constant value assigned to each cell in the model
'EFFECTIVE MOLECULAR DIFFUSION COEFFICIENT ----------------------------------'
        0 0.0000000 Constant value assigned to each cell in the model
```

### 8.3.4 Source-Sink Mixing (SSM) Package file

The SSM input file (rt3d.ssm in this example) lists the cells for which source-sink occurs. As recharge mass of $NO_3$ and P is added to RT3D internally within the SWAT-MODFLOW linking routines, there is nothing to change in this file.

```
Flag for constant concentration cells
F
```

### 8.3.5 Reaction (RCT) Package file

The RCT input file (rt3d.rct in this example) lists values for sorption and first-order denitrification:

```
'ISOTHM,IREACT,NCRXNDATA,NVRXNDATA,ISOLVER,IRCTOP -----------------------
1 10 2 0 1 0
Bulk density
0 1.855   Constant value assigned to each cell in the model
Sorption parameters
0 0.0           partition coefficient for NO3 (linear sorption)
0 3.5           partition coefficient for PO4 (linear sorption)       Sorption parameters assigned to
0 0.0           second parameter for NO3 (not used for linear sorption)  each cell in the model
0 0.0           second parameter for PO4 (not used for linear sorption)
Spatially Constant Values for reaction rates
0.10            kden  First-order rate constant for denitrification (1/T: needs same units as MODFLOW simulation)
10.00           kno3  Monod half-saturation term for denitrification
```

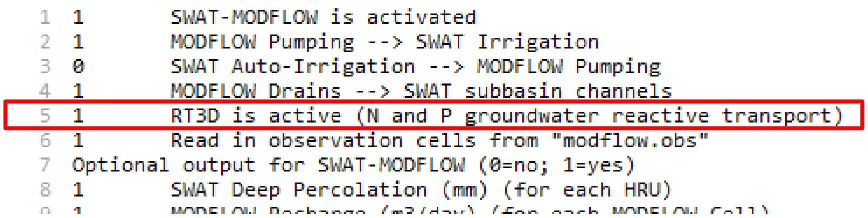
### 8.3.6 GCG Package file

The GCG input file (rt3d.gcg in this example) lists parameters for the implicit solver. Typically, these values should not be changed.

```
50 1 3 0                                  ITER1,MXITER,ISOLVE,NCRS
1.000 0.00001 0                           ACCL,CCLOSE,IPRGCG
```

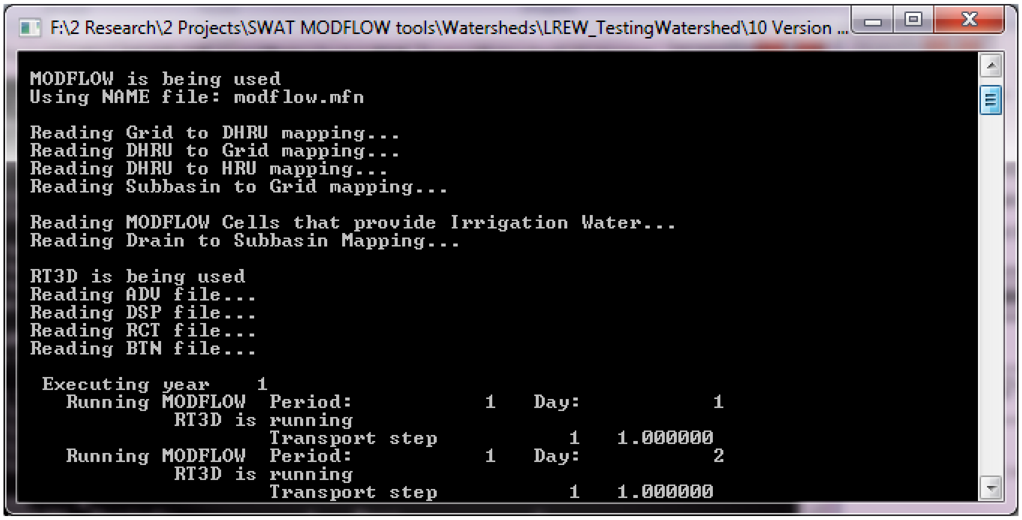
## 8.4 RUNNING SWAT-MODFLOW-RT3D

To activate RT3D within SWAT-MODFLOW, set the appropriate flag in swatmf_link.txt:



```
1        SWAT-MODFLOW is activated
1        MODFLOW Pumping --> SWAT Irrigation
0        SWAT Auto-Irrigation --> MODFLOW Pumping
1        MODFLOW Drains --> SWAT subbasin channels
1        RT3D is active (N and P groundwater reactive transport)
1        Read in observation cells from "modflow.obs"
Optional output for SWAT-MODFLOW (0=no; 1=yes)
1        SWAT Deep Percolation (mm) (for each HRU)
1        MODFLOW Recharge (m3/day) (for each MODFLOW Cell)
```

Then, double-click the SWAT-MODFLOW executable, as with other SWAT-MODFLOW simulations. The following dialog box will appear, with “RT3D is being used” written at the beginning of the simulation, and “RT3D is running” written for each daily time step. The transport step, i.e. the length of time for each RT3D calculation, also is reported as sometimes small time steps are required to solve the ADR equations. For most SWAT-MODFLOW simulations, however, the RT3D transport time step will be close to 1 day.



```
F:\2 Research\2 Projects\SWAT MODFLOW tools\Watersheds\LREW_TestingWatershed\10 Version ...

MODFLOW is being used
Using NAME file: modflow.mfn

Reading Grid to DHRU mapping...
Reading DHRU to Grid mapping...
Reading DHRU to HRU mapping...
Reading Subbasin to Grid mapping...

Reading MODFLOW Cells that provide Irrigation Water...
Reading Drain to Subbasin Mapping...

RT3D is being used
Reading ADV file...
Reading DSP file...
Reading RCT file...
Reading BTN file...

 Executing year     1
   Running MODFLOW  Period:           1    Day:           1
            RT3D is running
                    Transport step           1    1.000000
   Running MODFLOW  Period:           1    Day:           2
            RT3D is running
                    Transport step           1    1.000000
```

## 8.5 Viewing N and P Results

### 8.5.1 RT3D Output files

A number of output files are provided to view RT3D results. The following table lists the file names and associated content:

| RT3D Output File | | Units | Notes |
|---|---|---|---|
| **RT3D: Groundwater Concentration of $NO_3$ and P** | | | |
| | swatmf_out_RT_cno3_monthly | *mg/L* | Monthly averaged groundwater concentration for each active grid cell |
| | swatmf_out_RT_cp_monthly | *mg/L* | |
| | swatmf_out_RT_cno3_yearly | *mg/L* | Yearly averaged groundwater concentration for each active grid cell |
| | swatmf_out_RT_cp_yearly | *mg/L* | |
| | swatmf_out_RT_CONCNO3 | *mg/L* | Cell-by-cell output for the output times specified in the *.btn file |
| | swatmf_out_RT_CONCP | *mg/L* | |
| | swatmf_out_RT_OBSNO3 | *mg/L* | Output at each transport time step for the observation cells listed in the *.btn file |
| | swatmf_out_RT_OBSP | *mg/L* | |
| **RT3D: Recharge Water** | | | |
| | swatmf_out_RT_rechno3 | *mg/L* | Solute concentration in recharge water, for each grid cell |
| | swatmf_out_RT_rechP | *mg/L* | |
| **RT3D: Groundwater-Surface Water Loadings** | | | |
| | swatmf_out_RT_rivno3 | *kg/day* | Mass exchange between groundwater and surface water, for each River cell |
| | swatmf_out_RT_rivP | *kg/day* | |
| **SWAT: Recharge Water** | | | |
| | swatmf_out_SWAT_rechno3 | *mg/L* | Solute concentration in recharge water, for each HRU |
| | swatmf_out_SWAT_rechP | *mg/L* | |
| **SWAT: Groundwater-Surface Water Loadings** | | | |
| | swatmf_out_SWAT_rivno3 | *kg/day* | Mass exchange between groundwater and surface water for the RIVER package and the DRAIN package, for each subbasin |
| | swatmf_out_SWAT_rivP | *kg/day* | |

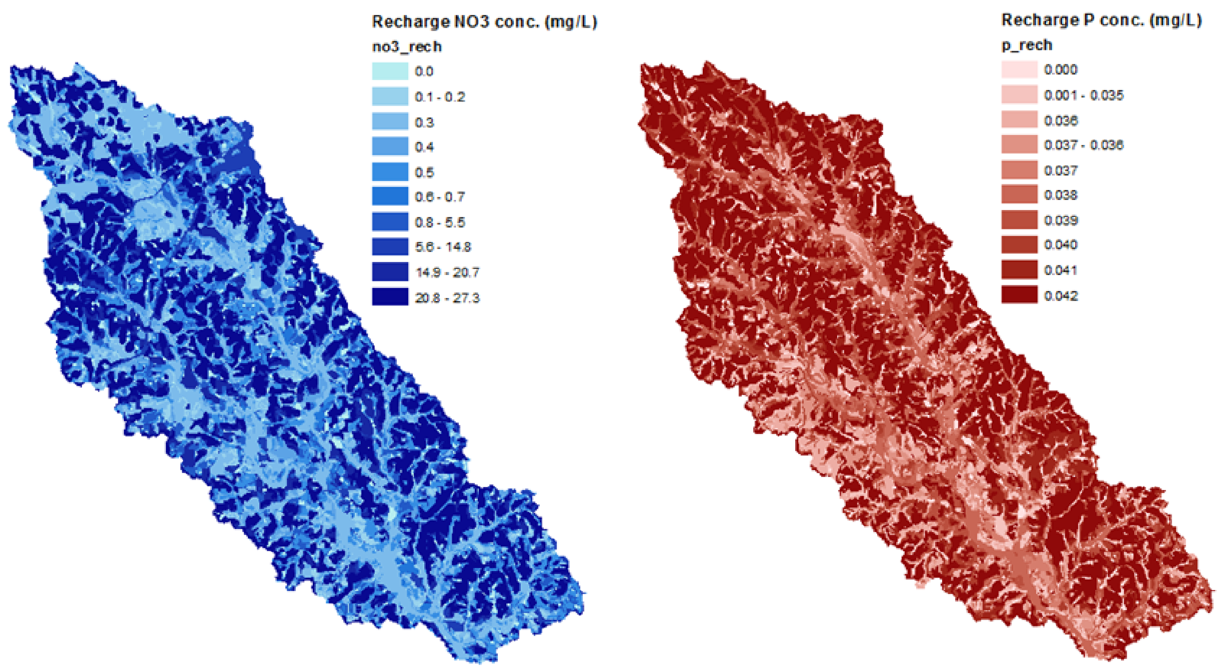
Output from these files can be used to prepare spatial plots of groundwater concentration or mass loadings to the streams, and time series of groundwater concentration:

*$NO_3$ and P Concentration in Recharge Water*

Files that can be used:

- swatmf_out_RT_rechno3
- swatmf_out_RT_rechP
- swatmf_out_SWAT_rechno3
- swatmf_out_SWAT_rechP

The following map shows the concentration of $NO_3$ and P in recharge water for each HRU, for day 361 of year 2002 in the simulation, as contained in the swatmf_out_SWAT_rechno3 and swatmf_out_SWAT_rechP files. The maps were prepared by adding the concentration values to the HRU shape file in ArcGIS.

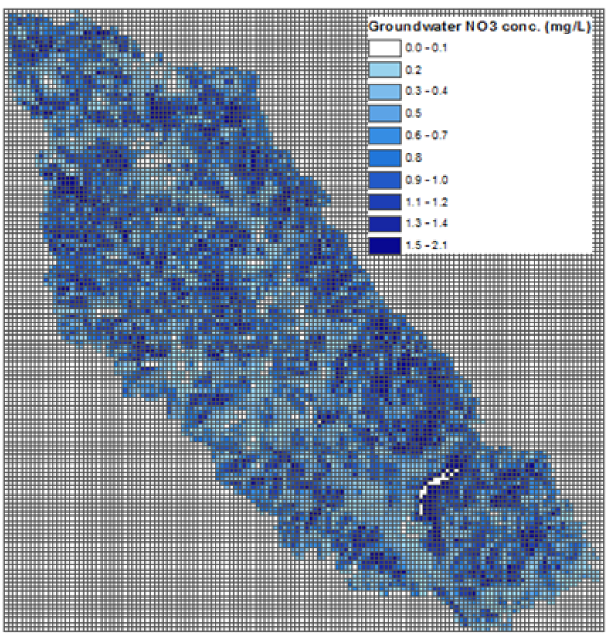


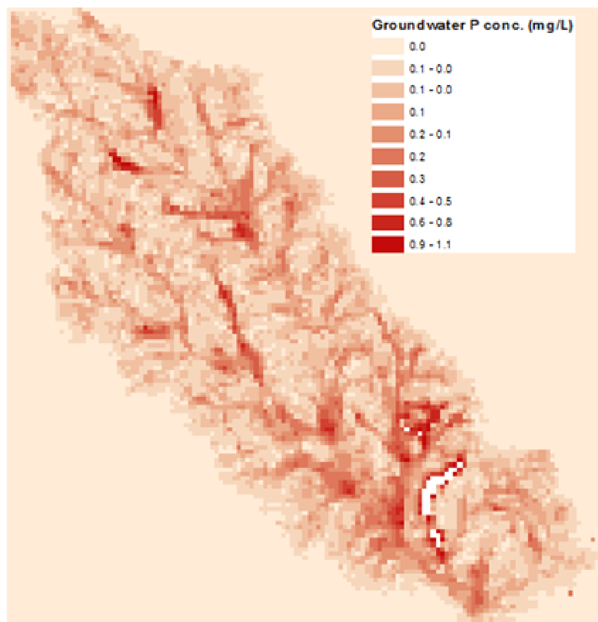
*$NO_3$ and P Concentration in Groundwater*

Files that can be used:

- swatmf_out_RT_cno3_monthly
- swatmf_out_RT_cp_monthly
- swatmf_out_RT_cno3_yearly
- swatmf_out_RT_cp_yearly
- swatmf_out_RT_CONCNO3
- swatmf_out_RT_CONCP

The following map shows the concentration of $NO_3$ and P in groundwater for each grid cell, for day 361 of year 2002 in the simulation, as contained in the swatmf_out_RT_CONCNO3 and swatmf_out_RT_CONCP files. The maps were prepared by adding the concentration values to the MODFLOW grid shape file in ArcGIS.

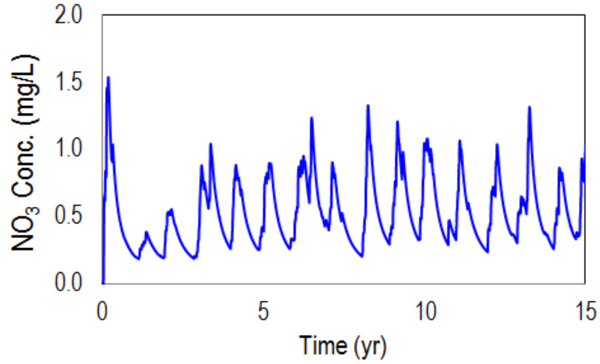


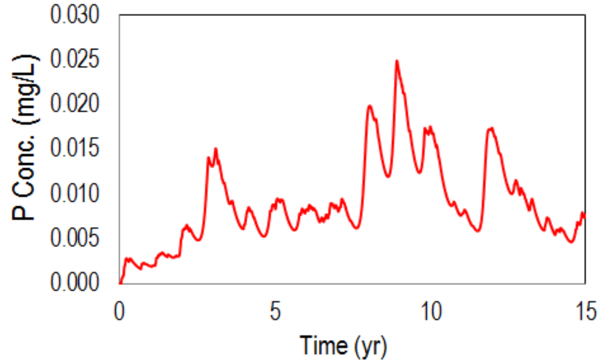



*$NO_3$ and P Concentration Time Series*
Files that can be used:

- swatmf_out_RT_OBSNO3
- swatmf_out_RT_OBSP

The following time series plots show the concentration of $NO_3$ and P at one location in the aquifer for each daily time step of the simulation. These plots can be compared to time series of measured groundwater concentration at groundwater monitoring wells.



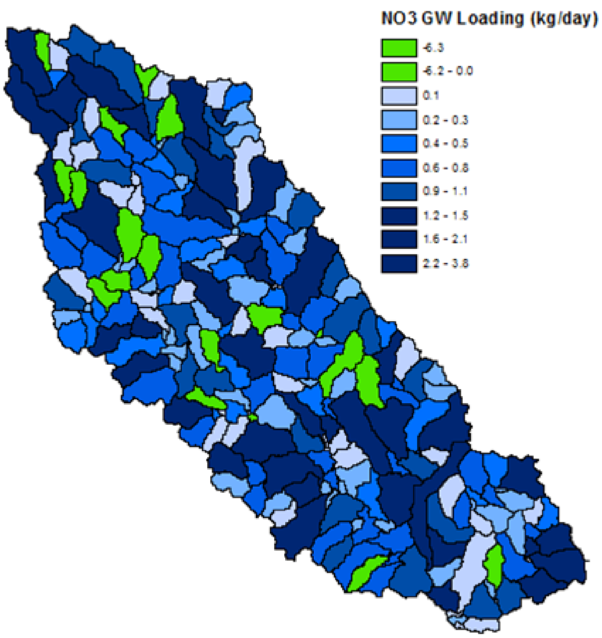



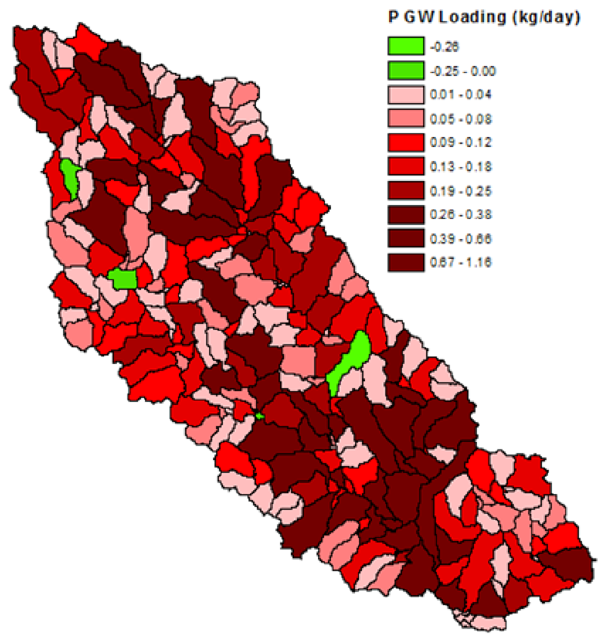
*$NO_3$ and P Mass Exchanges in Subbasins*

Files that can be used:

- swatmf_out_SWAT_rivno3
- swatmf_out_SWAT_rivP

The following maps show the loadings (kg/day) of $NO_3$ and P from the aquifer to SWAT subbasin channels, with values provided for each SWAT subbasin for a given day of the simulation. Light green polygons indicate SWAT subbasins where nutrient mass moves from the stream into the aquifer, as the stream is losing in these subbasins. These maps were prepared by adding values to the subbasins shape file in ArcGIS.



### 8.5.2 Daily, Monthly, Annual Values

The following variables (all in units of kg/ha) are added to the nutrient balance data in the SWAT file output.std:

NO3 GWQ: Mass loading of $NO_3$ from the aquifer to the stream network, via MODFLOW River Cells

NO3 SWGW: Mass loading of $NO_3$ from the stream network to the aquifer, via MODFLOW River Cells

NO3 DRN: Mass loading of $NO_3$ from the aquifer to the stream network, via MODFLOW Drain cells.

P GWQ: Mass loading of P from the aquifer to the stream network, via MODFLOW River Cells

P SWGW: Mass loading of P from the stream network to the aquifer, via MODFLOW River Cells

P DRN: Mass loading of P from the aquifer to the stream network, via MODFLOW Drain cells.

| WATER YIELD (mm) | SED YIELD (mm) | NO3 SURQ | NO3 LATQ | NO3 GWQ | NO3 SWGW | NO3 PERC | NO3 CROP | N ORGANIC | P SOLUBLE | P ORGANIC | P TILENO3 | P GWQ | P SWGW | NO3 DRN | P DRN |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | (kg nutrient/ha) | | | | | | | | | | | | | |
| 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| -0.13 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 0.13 | 0.01 | 0.00 | 0.01 | 0.00 | 0.01 | 0.00 | 0.00 | 0.03 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| -0.22 | 0.00 | 0.00 | 0.01 | 0.00 | 0.01 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| -0.36 | 0.00 | 0.00 | 0.01 | 0.00 | 0.04 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| -0.13 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| -0.16 | 0.00 | 0.00 | 0.01 | 0.00 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 1.23 | 0.05 | 0.00 | 0.01 | 0.00 | 0.01 | 0.00 | 0.00 | 0.09 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| -0.80 | 0.00 | 0.00 | 0.01 | 0.00 | 0.01 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 0.04 | 0.00 | 0.00 | 0.01 | 0.00 | 0.14 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 0.07 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

### 8.5.3 Average Annual Values

The tables of annual average values for nutrients at the end of the output.std file include the SWAT-MODFLOW variables for $NO_3$ and P loading for groundwater and drains. The following table is from the example simulation. The SWAT-MODFLOW-RT3D variables are boxed in blue.

```
NUTRIENTS
     ORGANIC N =      7.250 (KG/HA)
     ORGANIC P =      1.059 (KG/HA)
     NO3 YIELD (SQ) =      2.357 (KG/HA)
     NO3 YIELD (LAT) =     0.564 (KG/HA)
     NO3 YIELD (TILE) =     0.000 (KG/HA)
     SOLP YIELD (TILE) =    0.000(KG/HA)
     SOLP YIELD (SURF INLET RISER) =    0.000 (KG/HA)
     SOL P YIELD (SQ) =     0.074 (KG/HA)
     NO3 LEACHED =     15.742 (KG/HA)
     P LEACHED =      0.100 (KG/HA)
     N UPTAKE =    104.846 (KG/HA)
     P UPTAKE =    18.795 (KG/HA)
     NO3 LOAD GW (RT3D) =      0.750 (KG/HA)
     NO3 SW-GW (RT3D) =      1.225 (KG/HA)
     NO3 LOAD DRAIN (RT3D) =      0.020 (KG/HA)
     P LOAD GW (RT3D) =      0.078 (KG/HA)
     P SW-GW (RT3D) =      0.019 (KG/HA)
     P LOAD DRAIN (RT3D) =      0.001 (KG/HA)
```

*This concludes the tutorial.*

# REFERENCES


Bailey, R.T., Wible, T.C., Arabi, M., Records, R.M., and J. Ditty (2016), Assessing regional-scale spatio-temporal patterns of groundwater-surface water interactions using a coupled SWAT-MODFLOW model. *Hydrological Processes* 30(23), 4420-4433.

Clement, T.P. (1997), RT3D – A modular computer code for simulating reactive multi-species transport in 3-dimensional groundwater aquifer. Draft report. PNNL-SA-28967. Richland, Washington: Pacific Northwest National Laboratory.

Clement, T.P., Sun, Y., Hooker, B.S., and J.N. Peterson (1998), Modeling multispecies reactive transport in groundwater. *Groundwater Mon. & Rem.*, 18, 79-92.