CEE6400 Physical Hydrology

Homework 6. Terrain Analysis and TOPMODEL

Date: 10/31/16
Due: 11/9/16

Learning Objectives.

- Be able to use ArcGIS and TauDEM tools to derive hydrologically useful information from Digital Elevation Models (DEMs)
- Be able to describe the topographic wetness index used in TOPMODEL. (Rainfall Runoff Processes workbook chapter 6)
- Be able to use TOPMODEL principles to calculate soil moisture deficit and saturated areas as a function of wetness index and use this information in the calculation of runoff. (Rainfall Runoff Processes workbook chapter 6)

Assignment

1. Work through the material in **chapter 6** of the online Rainfall Runoff Processes module at http://www.engineering.usu.edu/dtarb/rrp.html and do the quiz at the end.
2. Do the TauDEM watershed delineation exercise below.
3. Do the Logan River Hydrologic Annual Water Balance and Runoff Ratio exercise below.
4. Do the Spawn Creek TOPMODEL exercise below

Computer Setup

Download and install TauDEM following the instructions at http://hydrology.usu.edu/taudem/taudem5/downloads.html. You will need administrator rights on the computer to do the installation. TauDEM is already installed in the ENGR PC lab (ENGR 302) if you do your work there.

2. TauDEM watershed delineation exercise

TauDEM (Terrain Analysis Using Digital Elevation Models) is a set of Digital Elevation Model (DEM) tools for the extraction and analysis of hydrologic information from topography as represented by a DEM. This is software developed at Utah State University (USU) for hydrologic digital elevation model analysis and watershed delineation and may be obtained from http://hydrology.usu.edu/taudem/taudem5/.

The purpose of this exercise is to introduce Hydrologic Terrain Analysis in ArcGIS using the TauDEM toolbox and to guide you through the initial steps of installing TauDEM loading data and running some of the more important functions required to delineate a stream network and watershed. This is a simplified version of tutorials given in the TauDEM documentation. Refer to the TauDEM documentation if you want to learn about other TauDEM functions (http://hydrology.usu.edu/taudem/taudem5/documentation.html).

In this exercise, you will perform the following tasks:

- Basic Grid Analysis using TauDEM functions
    - Pit Remove
    - D8 Flow Directions

- D8 Contributing Area
- Stream Network Analysis using TauDEM functions
    - Stream Definition by threshold
    - Stream Reach and Watershed

The Logan River watershed draining to USGS streamflow gauge 10109000 located just east of Logan, Utah is used as an example.

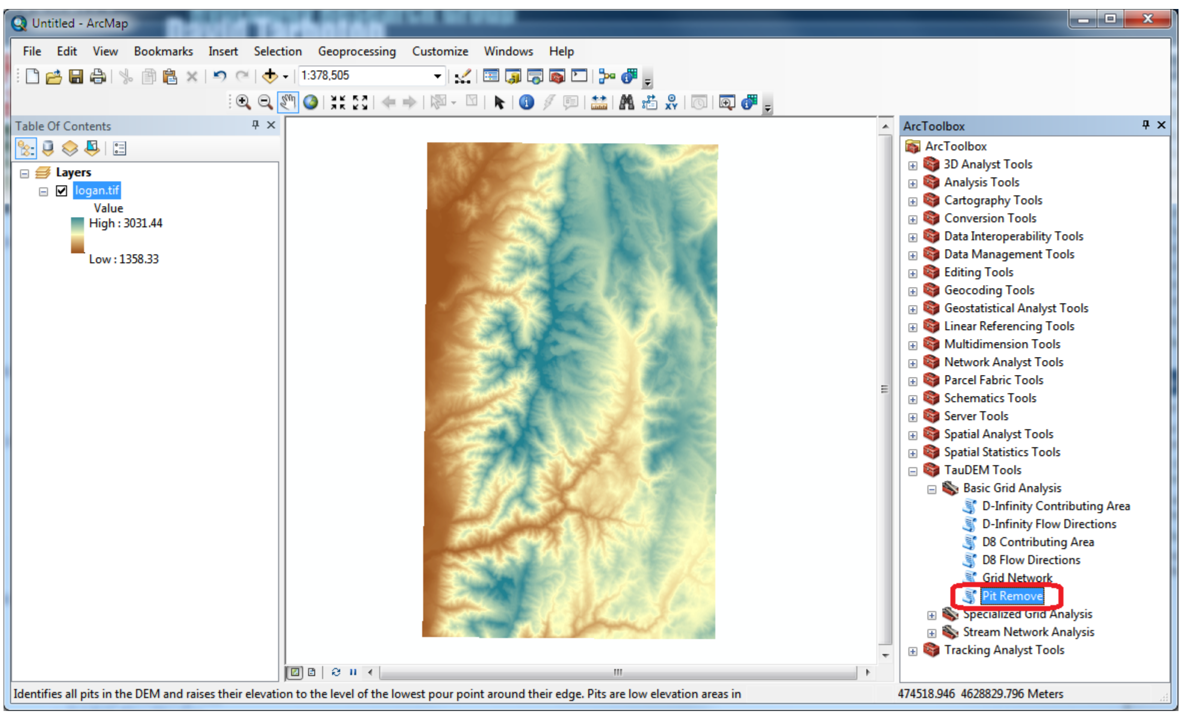
Basic Grid Analysis using TauDEM functions

In this section we illustrate the TauDEM basic grid analysis functions.

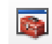
1. Download the Logan River Exercise data zip file from Canvas (Logan.zip). Extract all files from the zip file. Open ArcMap and add the digital elevation model (DEM) grid file **logan.tif** into ArcMap.

This digital elevation model (DEM) data was obtained from the National Elevation Dataset available from the national map (http://viewer.nationalmap.gov/viewer/), then projected and converted to the TIFF format used as a default by TauDEM. (To learn about map projections in GIS see http://desktop.arcgis.com/en/arcmap/latest/map/projections/what-are-map-projections.htm. To learn how to convert files to TIFF format see http://hydrology.usu.edu/taudem/taudem5/TauDEM53GettingStartedGuide.pdf).

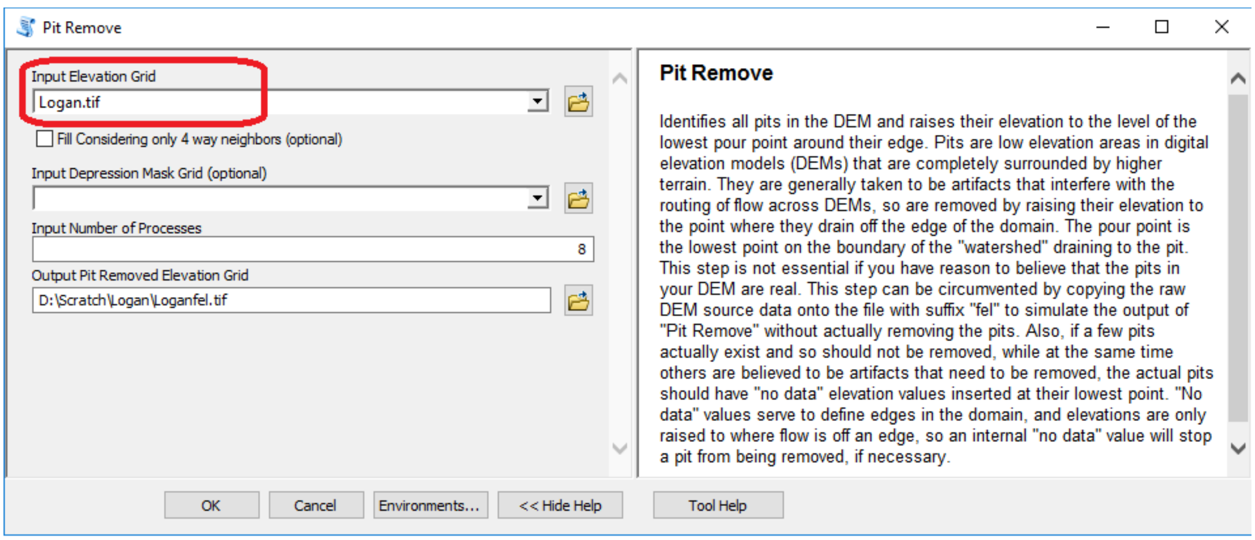
In the below I have used symbology to select a different color scheme.



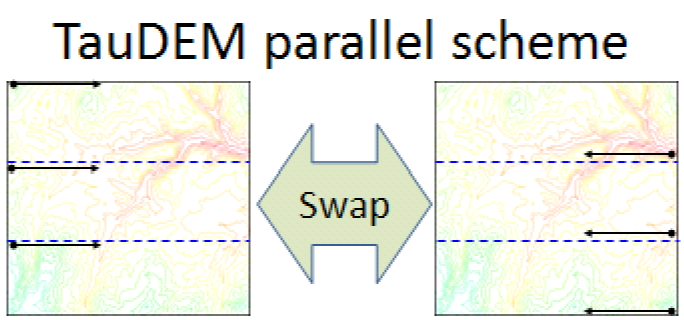
The first TauDEM function used is Pit Remove. Pits are grid cells surrounded by higher terrain that do not drain. Pit Remove creates a hydrologically conditioned DEM by raising the elevation of pits to the point where they overflow their confining pour point and can drain to the edge of the domain. PitRemove is located in the TauDEM Tools Basic Grid Analysis group illustrated above. If you do not find this in ArcMap, and TauDEM has been installed, you may need to add the TauDEM toolset to your document

1. If the ArcToolbox Window is not open, click on the Toolbox icon  in the Standard Toolbar
2. Right click on ArcToolbox at the top of the toolbox window. Select Add Toolbox... .
3. Browse to the TauDEM install directory (usually C:\Program Files\TauDEM\ TauDEM5Arc\).
4. Click on the TauDEM_Tools.tbx file, and click Open.
5. If you wish right click on the ArcToolbox at the top and save settings to default so as not to have to do this again

2. Open (by double clicking) the TauDEM **Pit Remove** Tool. Select **logan.tif** for the Input Elevation Grid. Note that the Output Pit Removed Elevation Grid is automatically filled with loganfel.tif following the file naming convention. You may adjust or leave the number of processes at 8.



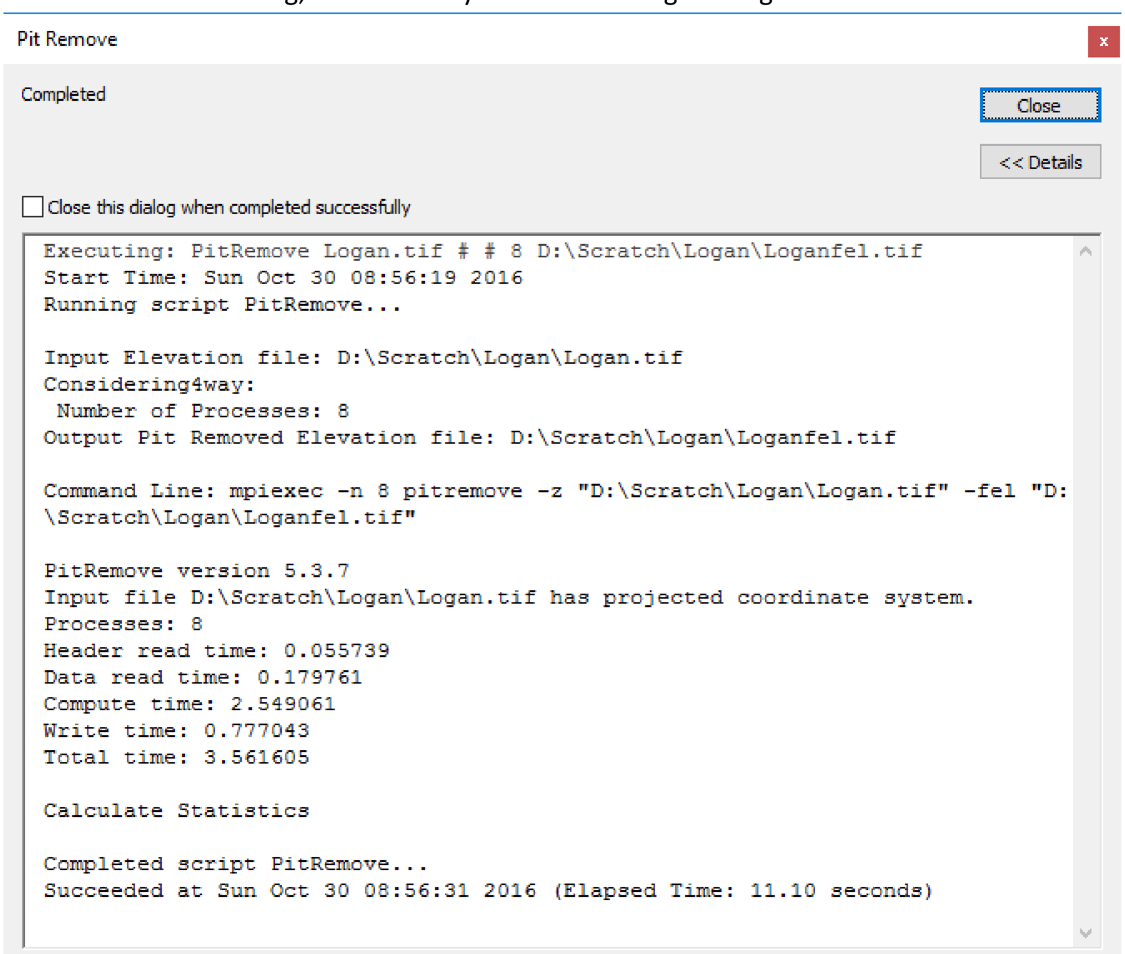
The parallel approach used by TauDEM is illustrated below.



The domain is subdivided into row oriented partitions that are each processed independently by separate processes. When the algorithms reach a point where they can proceed no further within the partitions there is a swap step that exchanges information along the boundaries. The algorithms then proceed working within the partitions using new boundary information. This process is iterated until completion. The strategies for sharing information across boundaries and iterating are specific to each algorithm.

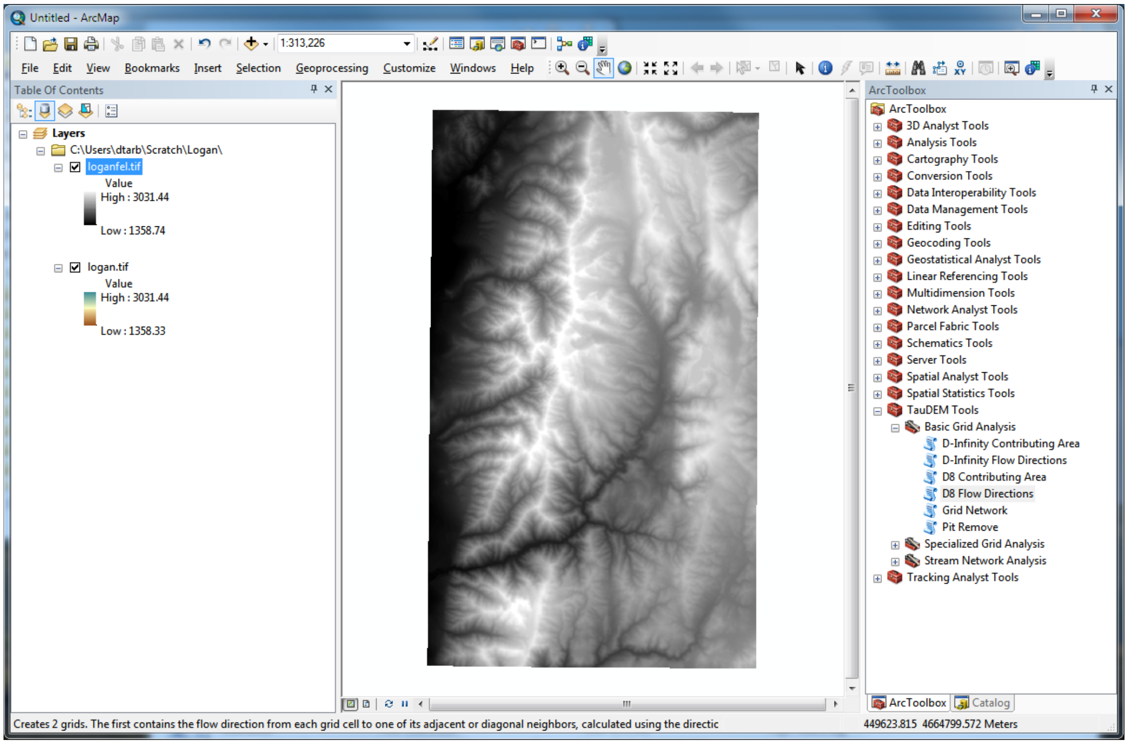
The number of processes does not have to be the same as the number of processors on your computer, although generally should be the same order of magnitude. The operating system (and MPI) takes care of time sharing between processes, so in cases where some processes are likely to be waiting for other processes to complete there may be a benefit in selecting more processes than physical processors on the computer. However then message passing across the borders is increased. For large datasets, some experimentation as to the number of processes that works best (fastest) is suggested. For this exercise the functions run quickly and the number of processes does not matter too much.

3. Click OK on the Pit Remove tool to run the Pit Remove function. The output dialog reports run statistics that include timing, as well as any error or warning messages.

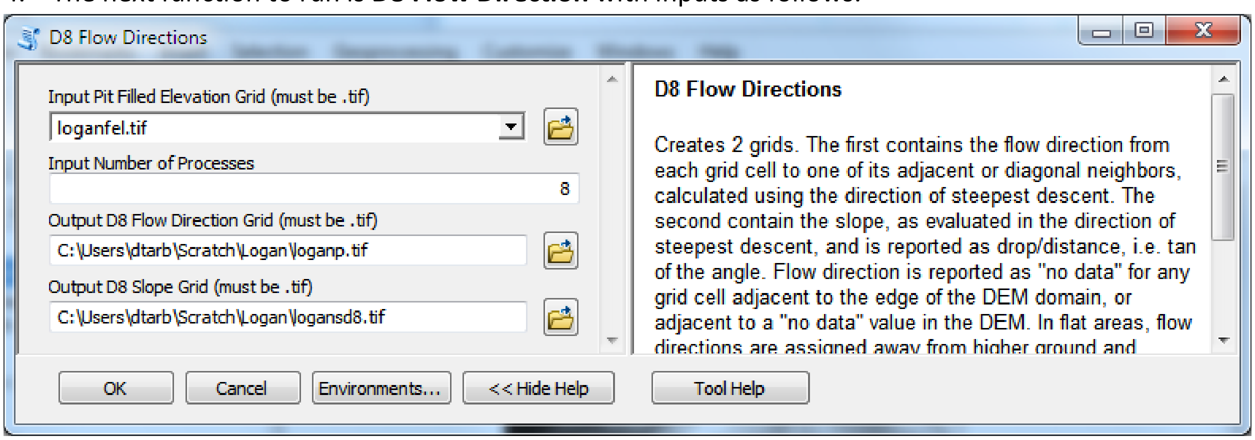


Clicking OK to run each tool will be implied from here on if not stated.

The result is a new grid layer loganfel.tif that has been added to the ArcMap Document.

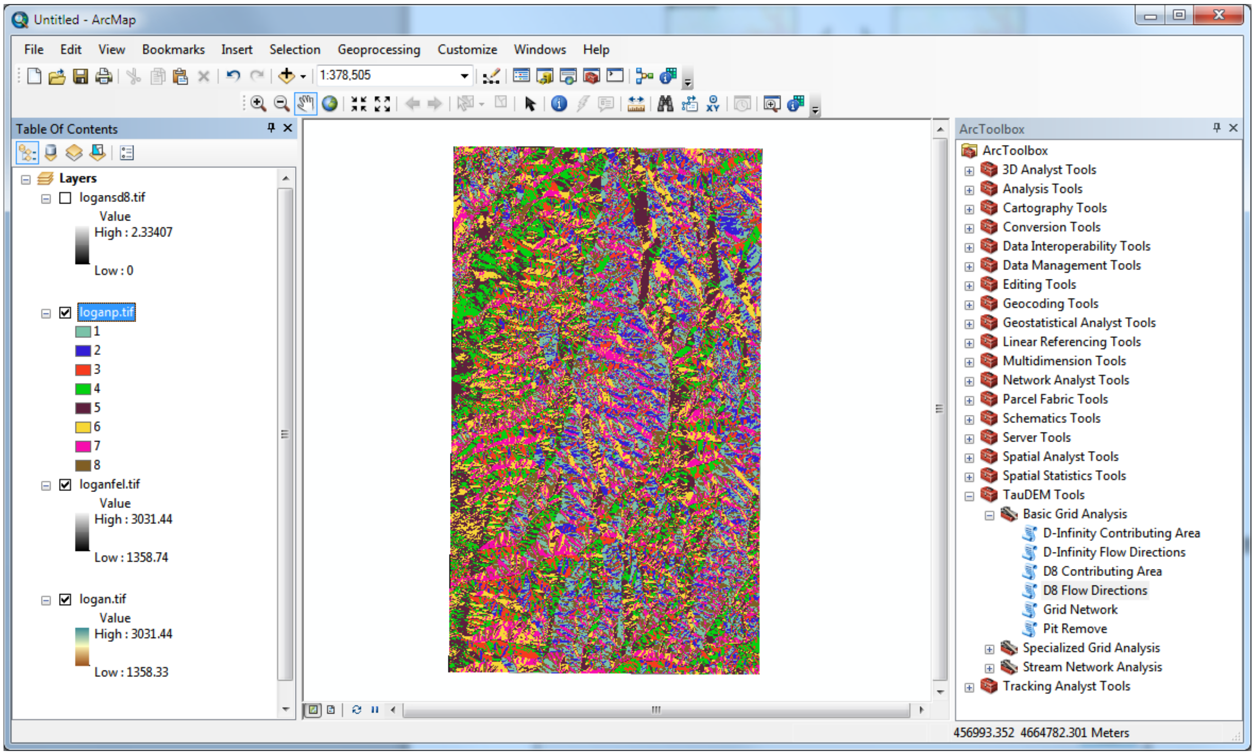


4. The next function to run is **D8 Flow Direction** with inputs as follows.

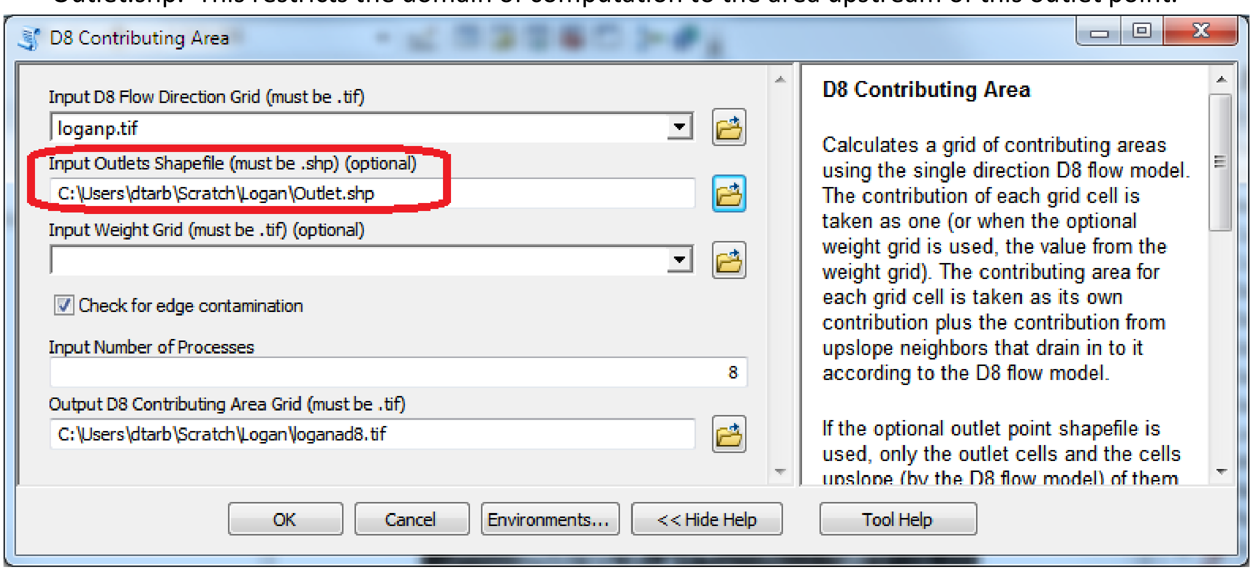


This takes as input the hydrologically conditioned elevation grid and outputs D8 flow direction and slope for each grid cell. The resulting D8 flow direction grid (name has suffix p) is illustrated. This is an encoding of the direction of steepest descent from each grid cell using the numbers 1 to 8 (counter clockwise from east). This is a simple model for the direction of water flow over the terrain.

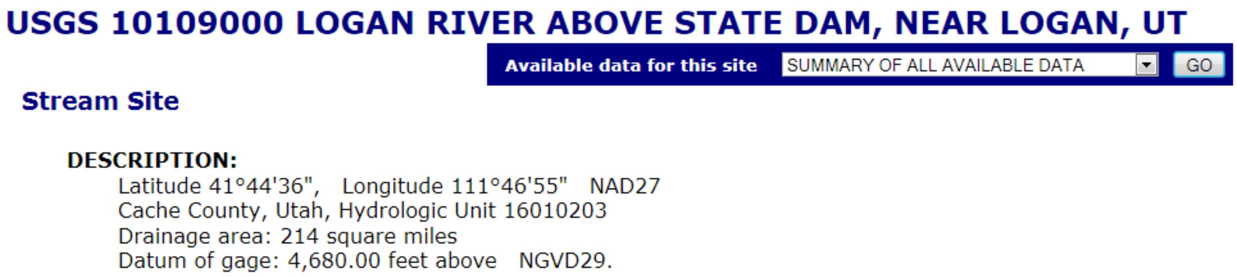
To get the display below the symbology of loganp.tif was changed to show unique values.



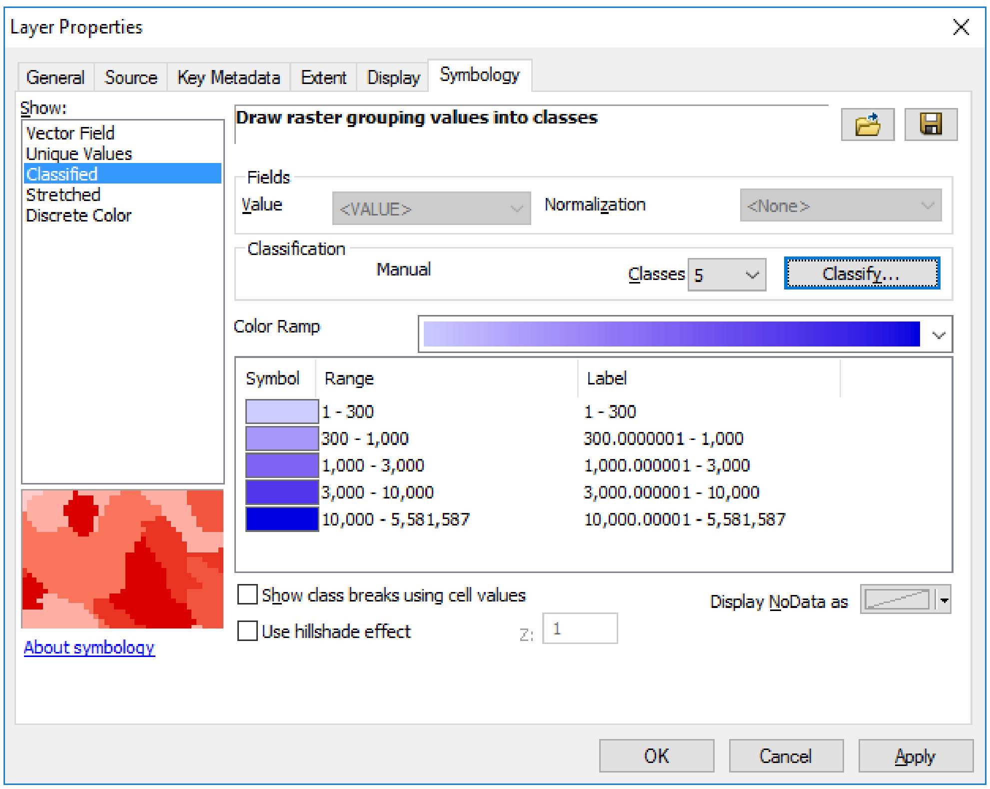
5. The next function to run is **D8 Contributing Area**. This function counts the number of grid cells draining through (out of) each grid cell based on D8 flow directions. Set the Outlets shapefile to Outlet.shp. This restricts the domain of computation to the area upstream of this outlet point.



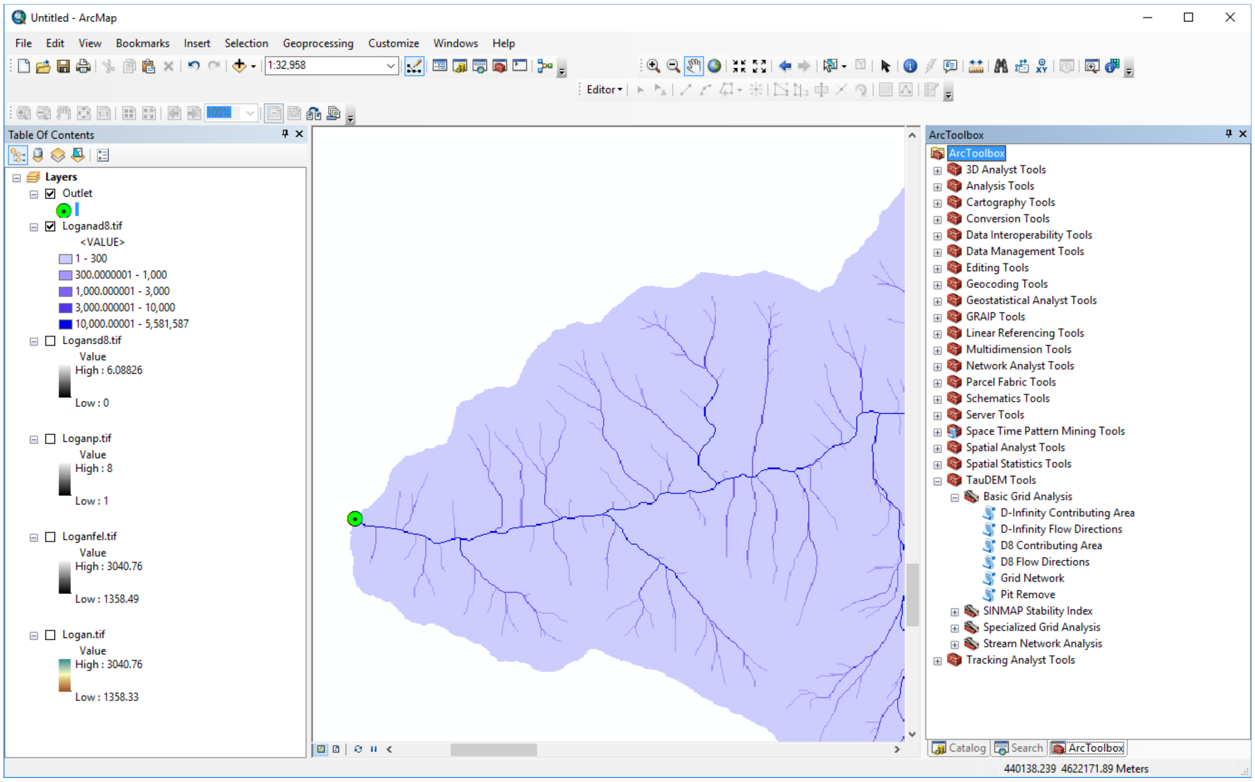
The outlet point provided in the file Outlet.shp is at the location of the Logan River Stream Gauge based on latitude and longitude from the USGS NWIS information for that gauge (http://waterdata.usgs.gov/nwis/inventory/?site_no=10109000&agency_cd=USGS&)



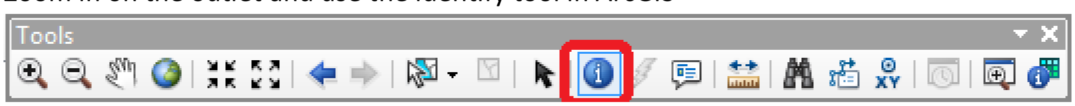
A classified symbology with multiplicative class ranges (100, 300, 1000, 3000 etc.) is often best to render contributing area values as in the illustration below.



In the below I have added the Outlet.shp shapefile and zoomed to the area near the outlet to illustrate how watershed area has only been evaluated upstream of the outlet.



Zoom in on the outlet and use the identify tool in ArcGIS



to identify the value of *loganad8.tif* at the location of the outlet. Examine the properties of *loganad8.tif* and determine its cell size.

To turn in:

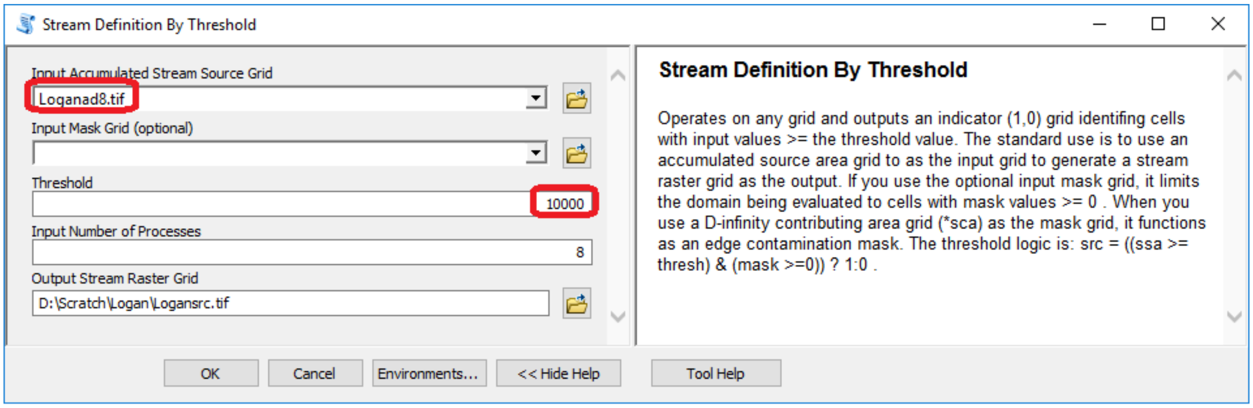
1. *Report the contributing area draining to the outlet location in number of cells, square kilometers and square miles. Report the area of a single grid cell. Compare your result in square miles to the USGS drainage area value for this site.*

Save your map document, to save your work. It is good practice to do this often in case of a crash.

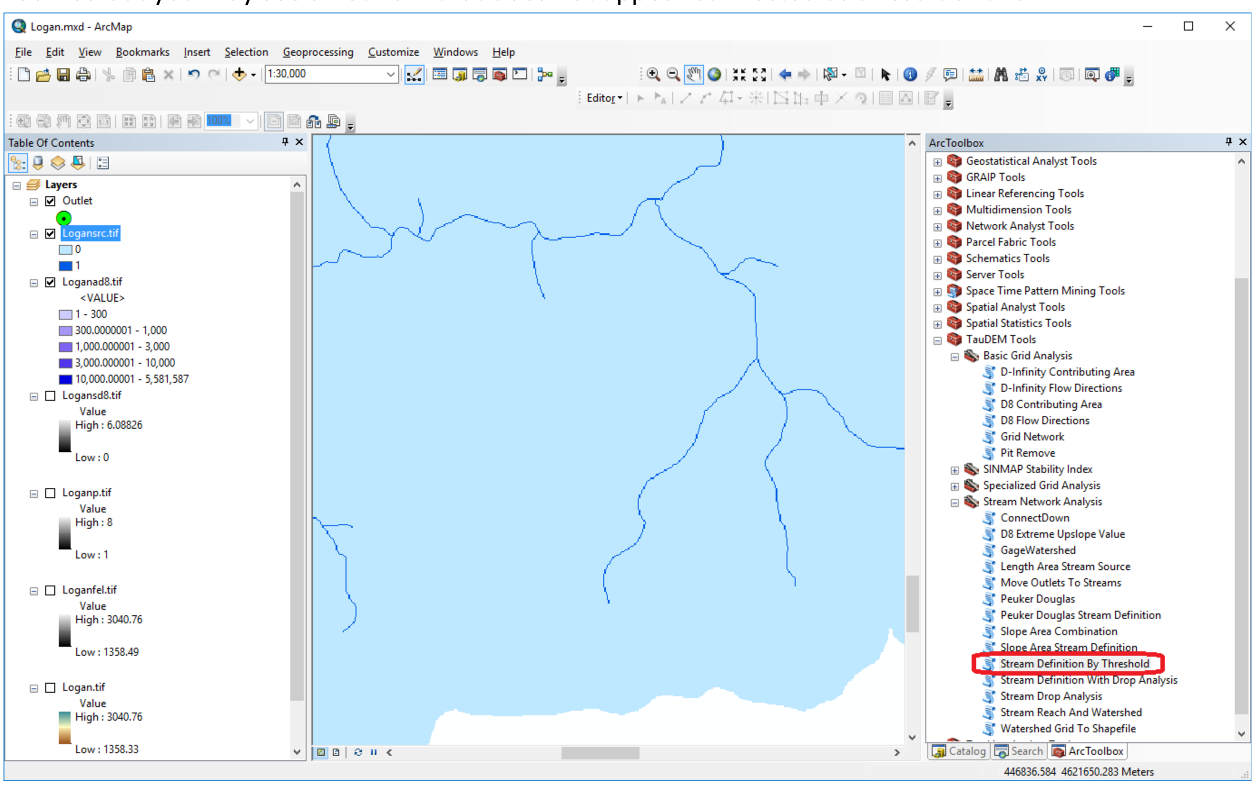
Stream Network Analysis using TauDEM functions

TauDEM provides a number of methods for delineating and analyzing stream networks and watersheds. The simplest stream network delineation method uses a threshold on contributing area.

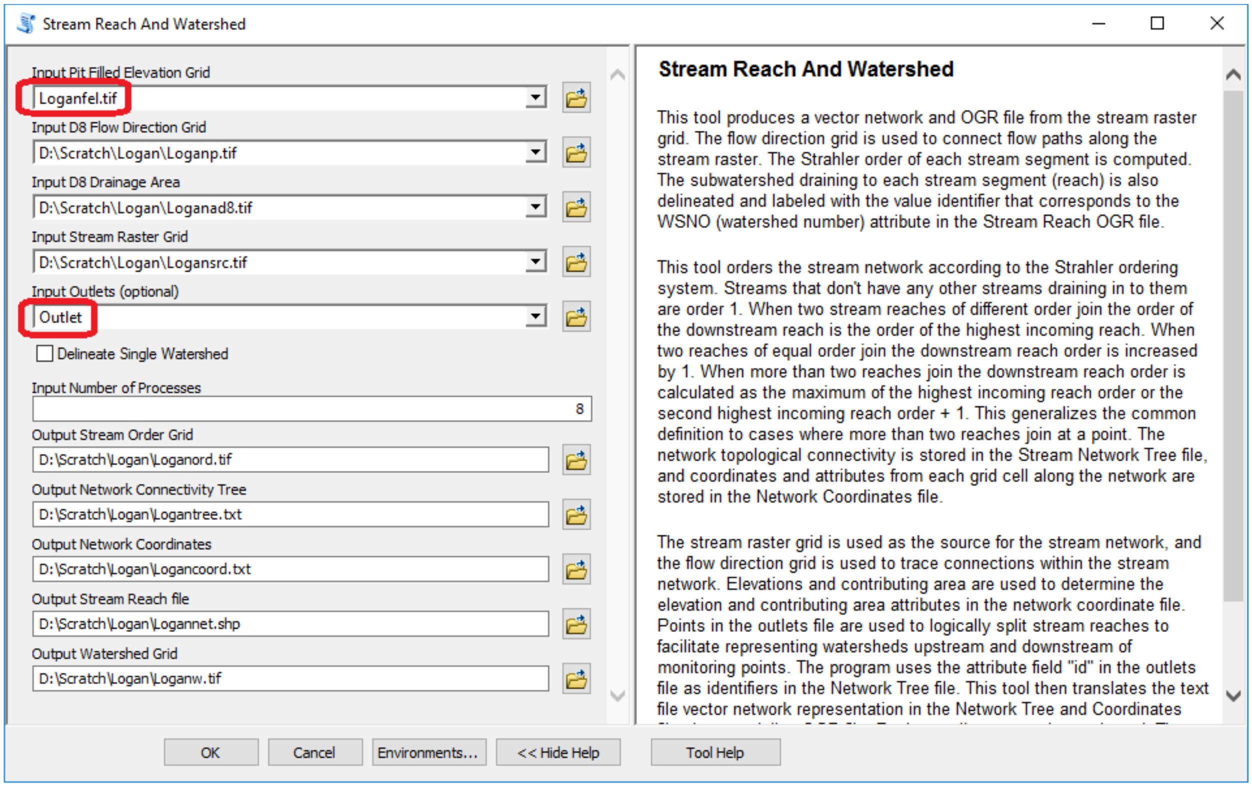
6. **Stream Definition by Threshold.** This function (in the stream network analysis tool group) defines a stream raster grid (src suffix) by applying a threshold to the input. In this case the input is a D8 contributing area grid and a threshold of 1000 grid cells has been used.



The result depicts the stream network (but is not logically connected as a network shapefile yet). When zoomed out you may see a network that does not appear connected as a result of this.

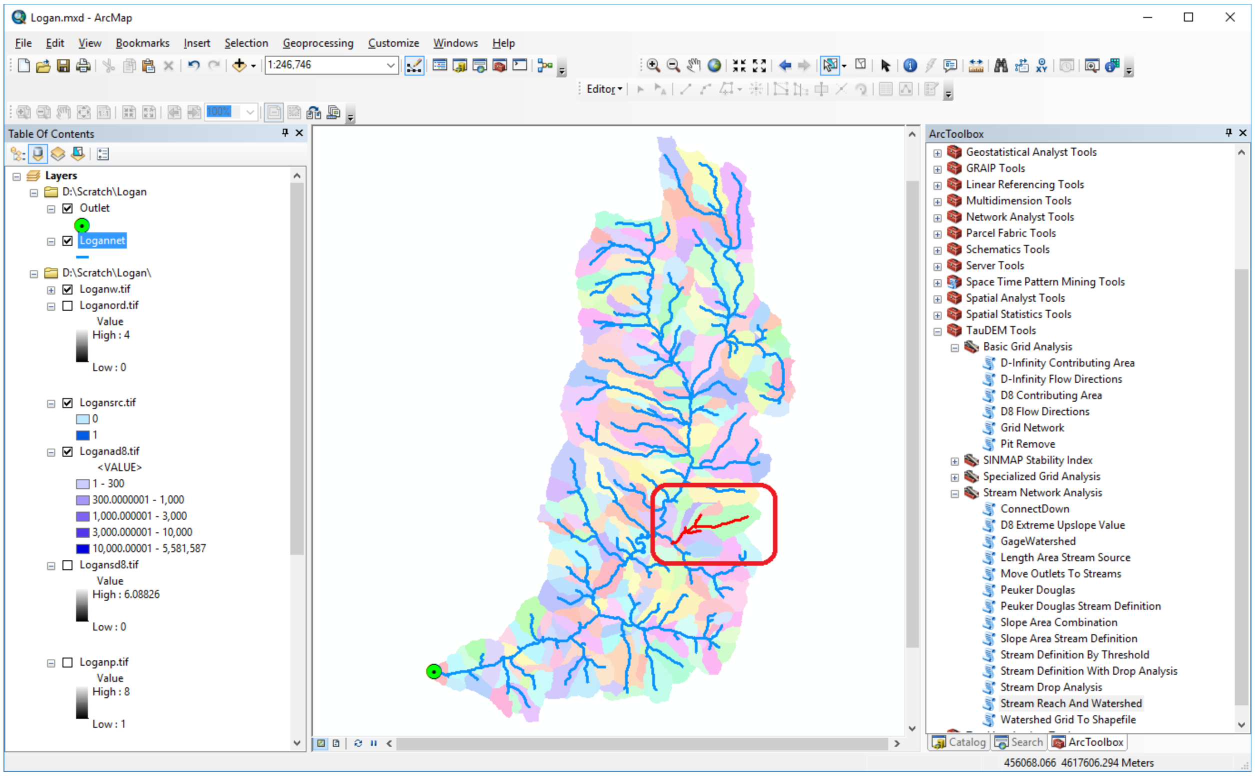


7. **Open Stream Reach and Watershed** and select the following inputs. Note that if you select just those indicated the others complete automatically. Don't forget to select the Outlet.



You should see a shapefile Logannet.shp, subwatershed raster Loganw.tif and stream order raster Loganord.tif added to your map. You can symbolize these as desired. The display should be similar to the below, except without the highlighting of the area around Spawn Creek.

The subwatershed raster and stream network shapefile are key outputs from TauDEM. Each link in the stream network has a unique identifier that is linked to downstream and upstream links. Each subwatershed also has a unique identifier that is referenced in terms of the stream network that it drains to. This information enables construction of a subwatershed based distributed hydrologic model with flow from subwatersheds being connected to, accumulated in, and routed along the appropriate stream reaches.



Zoom in on the area around Spawn Creek (see red box above) and examine the properties of the stream network and subwatersheds in this area. There should be nine stream links that form the Spawn Creek tributary network.

To turn in:

2. *Prepare a table that reports for the 9 stream links in the Spawn Creek tributary of the stream network the following attributes:*
    - *Link number*
    - *Downstream link number*
    - *Upstream link number 1*
    - *Upstream link number 2*
    - *Downstream contributing area*
    - *Length*
    - *Identifier of corresponding watershed (WSNO)*
3. *Open the attribute table of loganw.tif and identify the count (number of grid cells) of the 9 Spawn Creek subwatersheds. Based on this count calculate area of each subwatershed and reconcile your values with contributing area values in the table from the stream network.*
4. *Prepare a diagram that shows, based on your answers to 2 and 3, how connectivity between subwatersheds, stream links and upstream and downstream links is encoded.*

3. Logan River Hydrologic Annual Water Balance and Runoff Ratio exercise.

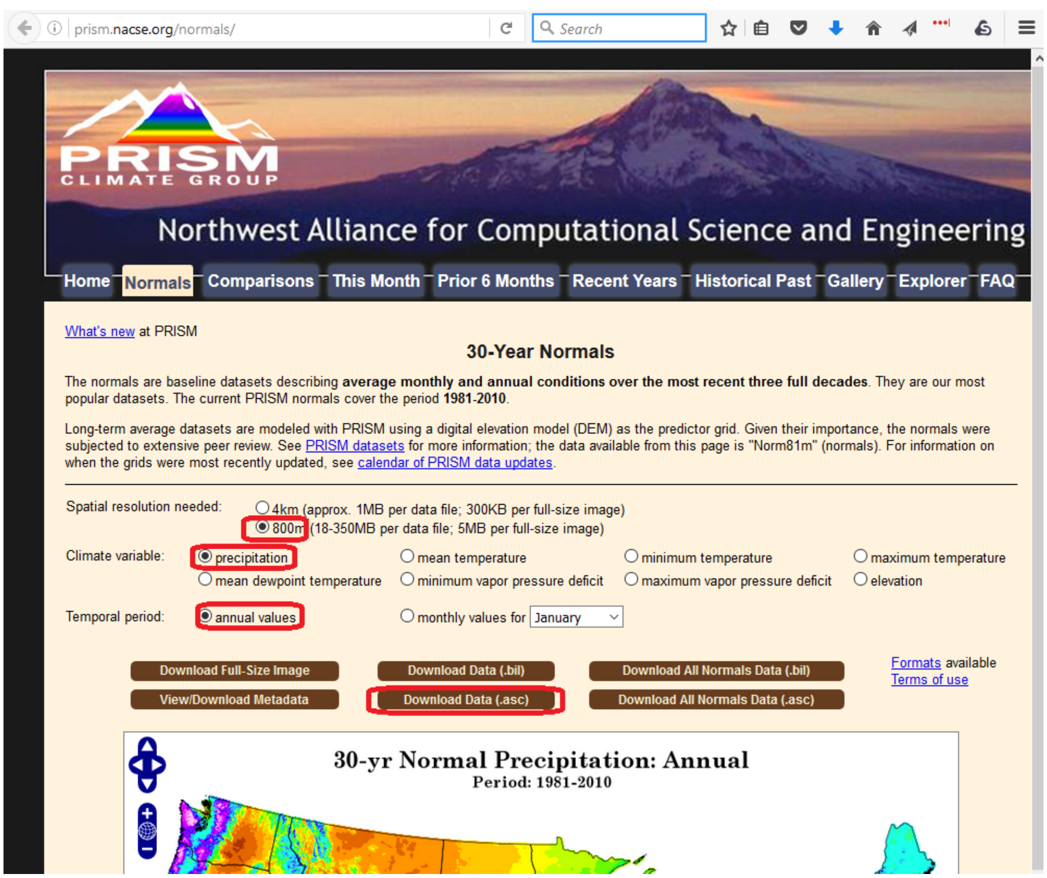
Important quantities in the water balance of a watershed are the streamflow, expressed on a per unit area basis, area average precipitation and the runoff ratio r=q/P. Let's determine these for the Logan River. Streamflow we will get from the USGS. Precipitation we will get from Oregon State University (PRISM).

Use the USGS NWIS website for Logan River above state dam (10109000) http://waterdata.usgs.gov/nwis/nwisman/?site_no=10109000&agency_cd=USGS to determine mean annual streamflow for the years 1981-2010. These years chosen for consistency with PRISM. Select annual statistics on this website and specify the period of record. Then copy the data for each year to a spreadsheet and calculate the 30 year average. Per unit area discharge is

$$q = \frac{Q}{A}$$

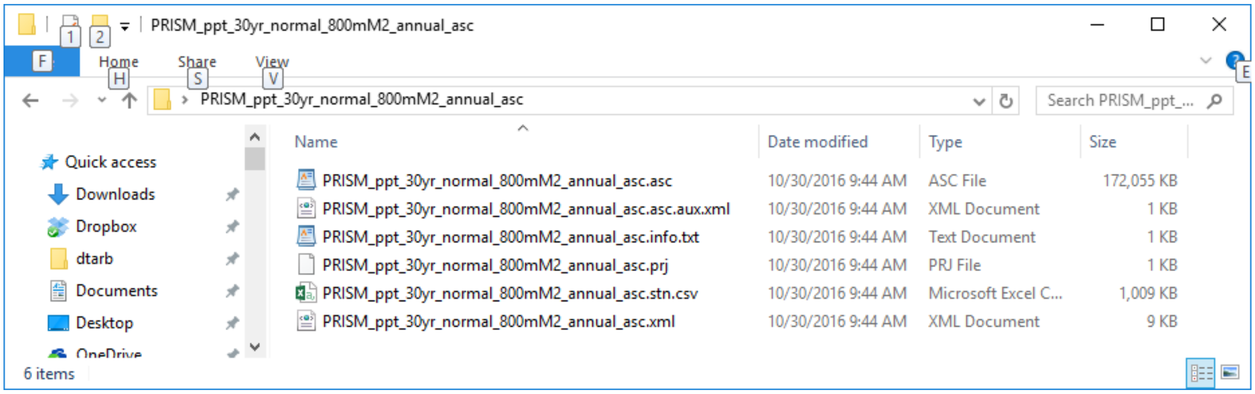
Do the necessary unit conversions to express this in mm.

PRISM Precipitation data. From the Oregon State University PRISM website: http://prism.nacse.org/normals/ select precipitation and annual values and click on Download Data (.asc)



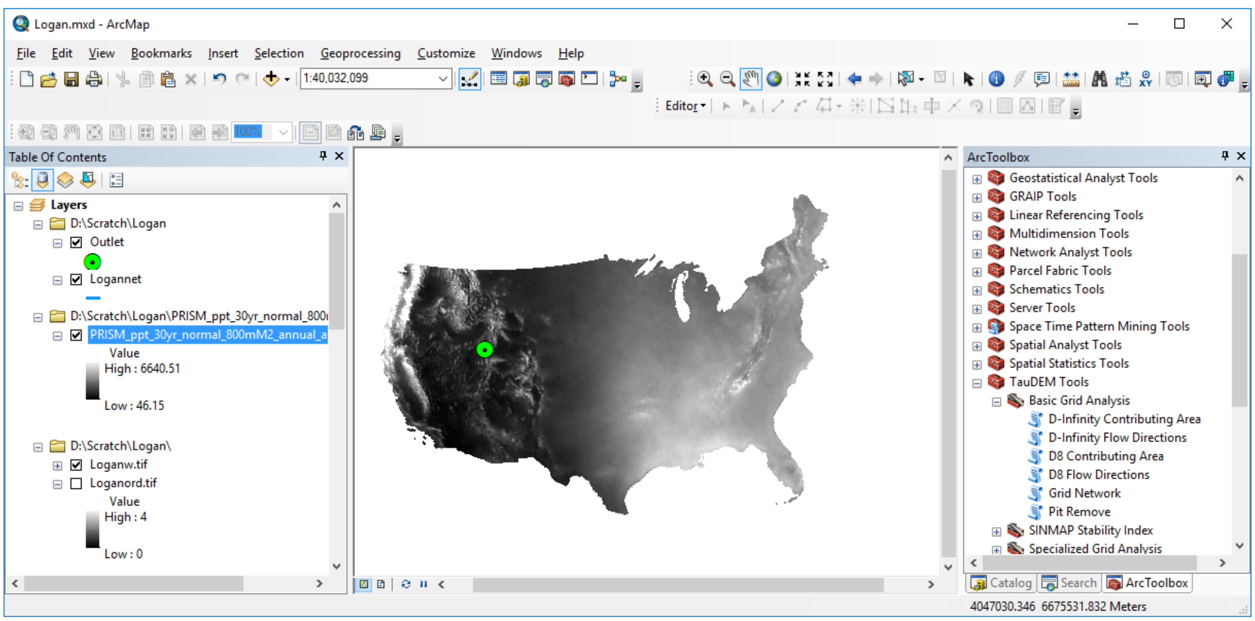
You should receive a file PRISM_ppt_30yr_normal_800mM2_annual_asc.zip.

Use a zip utility (I use 7zip) to uncompress this file. The contents are:

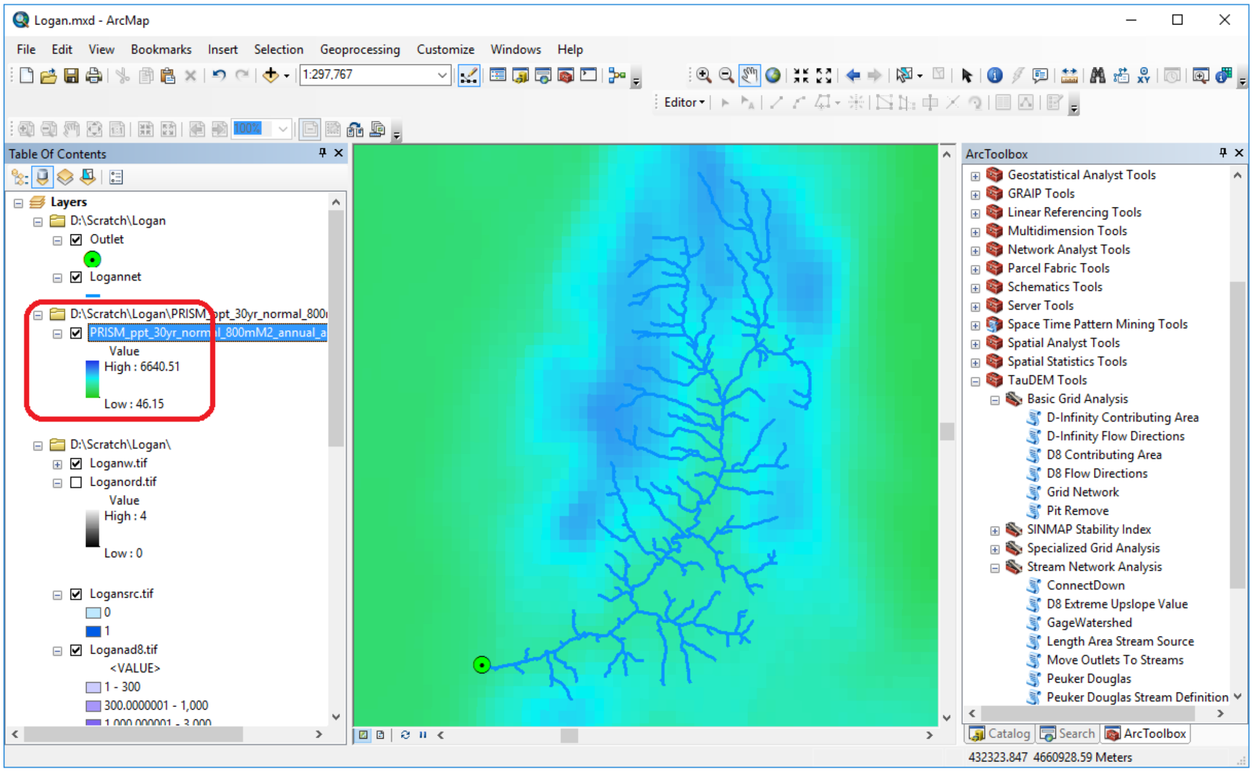


In ArcGIS use **+ Add data** to add the file PRISM_ppt_30yr_normal_800mM2_annual_asc.asc.

This adds the 30-year normal precipitation values to ArcMap. If you zoom out, you see they cover the entire country.

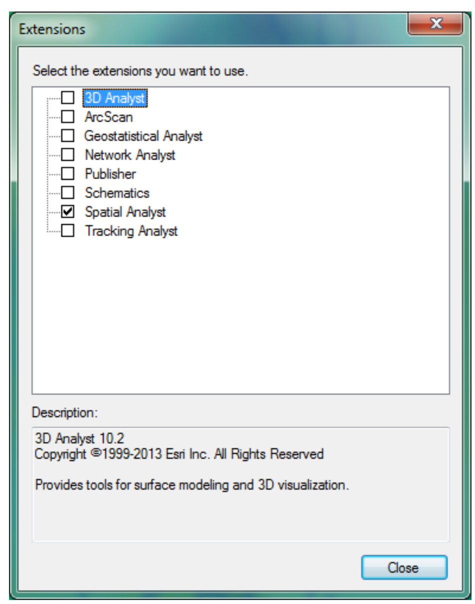


Zoom back in to the Logan River Basin and symbolize PRISM precipitation in a way to see the pattern. I have symbolized it green to blue

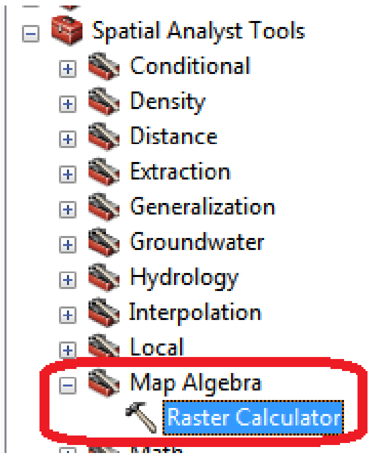


Notice the higher precipitation values in the mountains. Notice also the data values in the legend table of contents. These values are in mm (stated in one of the accompanying XML files).

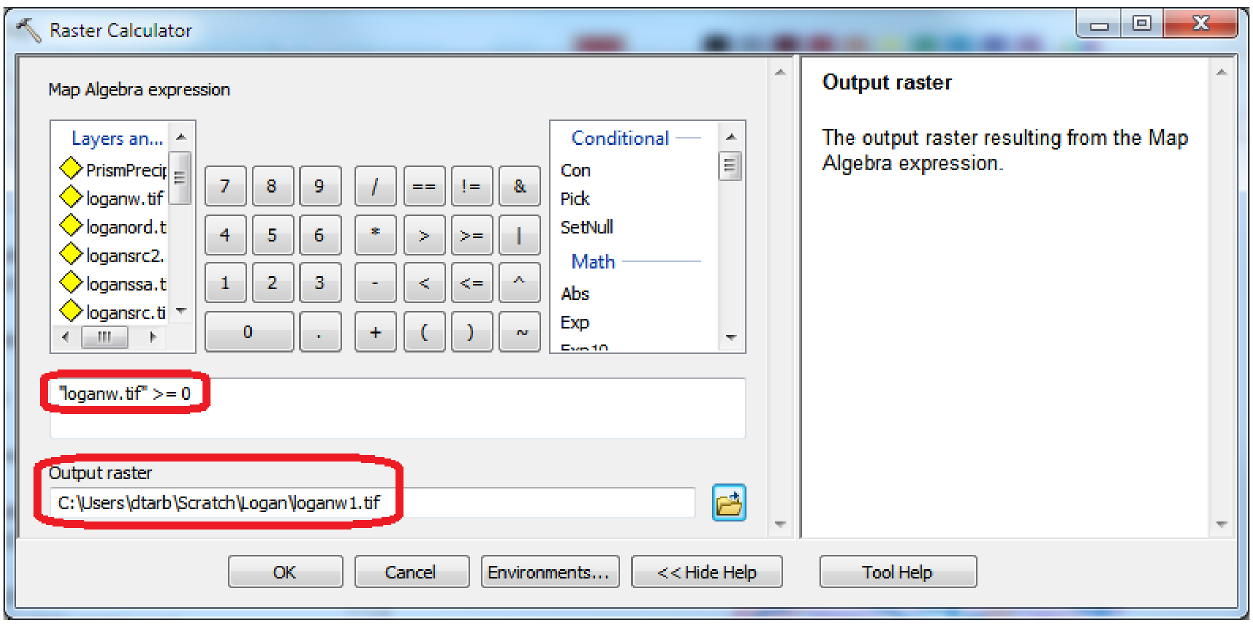
Next we would like to average this data over the Logan River Watershed. To do this we need a single file specifying the "zone" that is the Logan River watershed. The file loganw.tif defines subwatersheds. Make sure that under Customize Extensions, Spatial Analyst is checked.



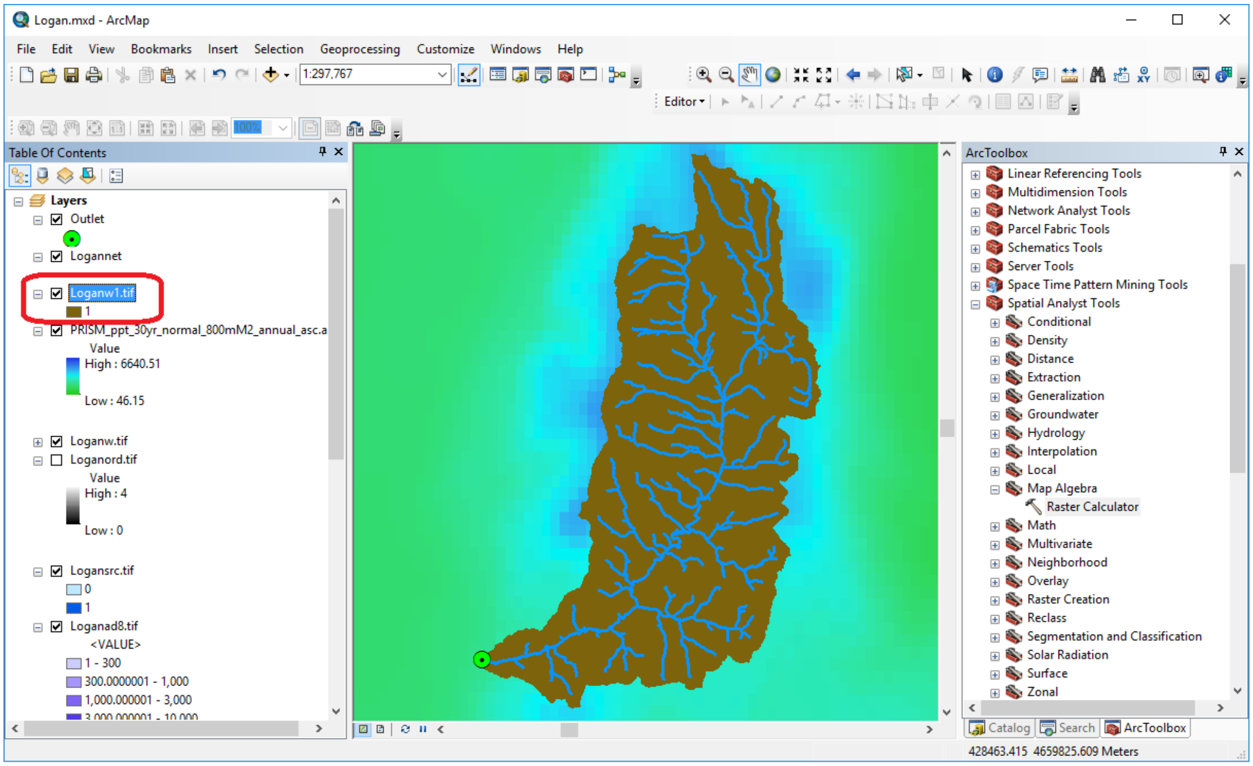
Use the Raster Calculator Tool



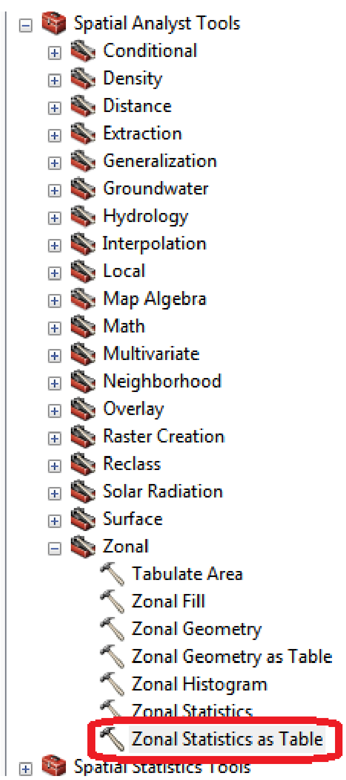
with the following inputs



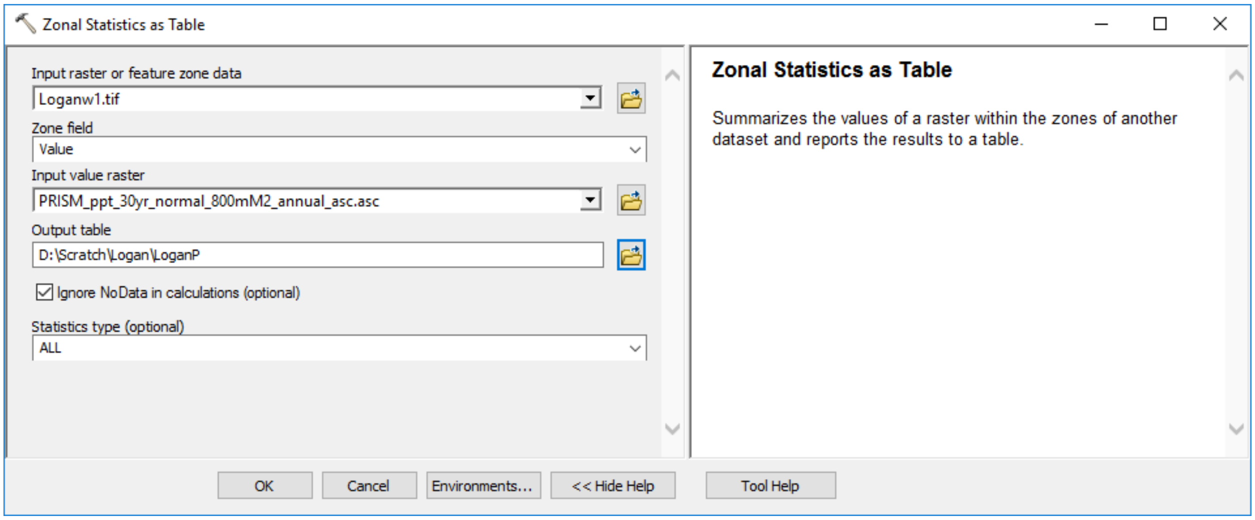
The result is a grid layer **loganw1.tif** that has a value of 1 over the Logan River watershed and is undefined everywhere else



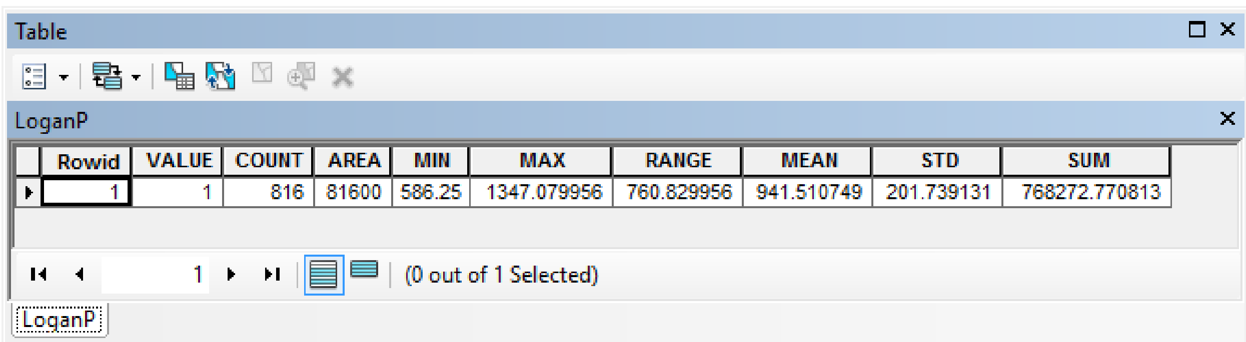
Use the Zonal Statistics as Table tool



with the following inputs



The result is a table giving precipitation statistics averaged over the Logan River Watershed.



Rowid	VALUE	COUNT	AREA	MIN	MAX	RANGE	MEAN	STD	SUM
1	1	816	81600	586.25	1347.079956	760.829956	941.510749	201.739131	768272.770813

The mean rainfall over the Logan Watershed can be read as 941.5 mm. (Beware. Sometimes in ArcMap table displays you need to widen the column displays to get all digits displayed and interpret the data correctly).

Calculate the runoff ratio for the Logan River

$$r = \frac{q}{P}$$

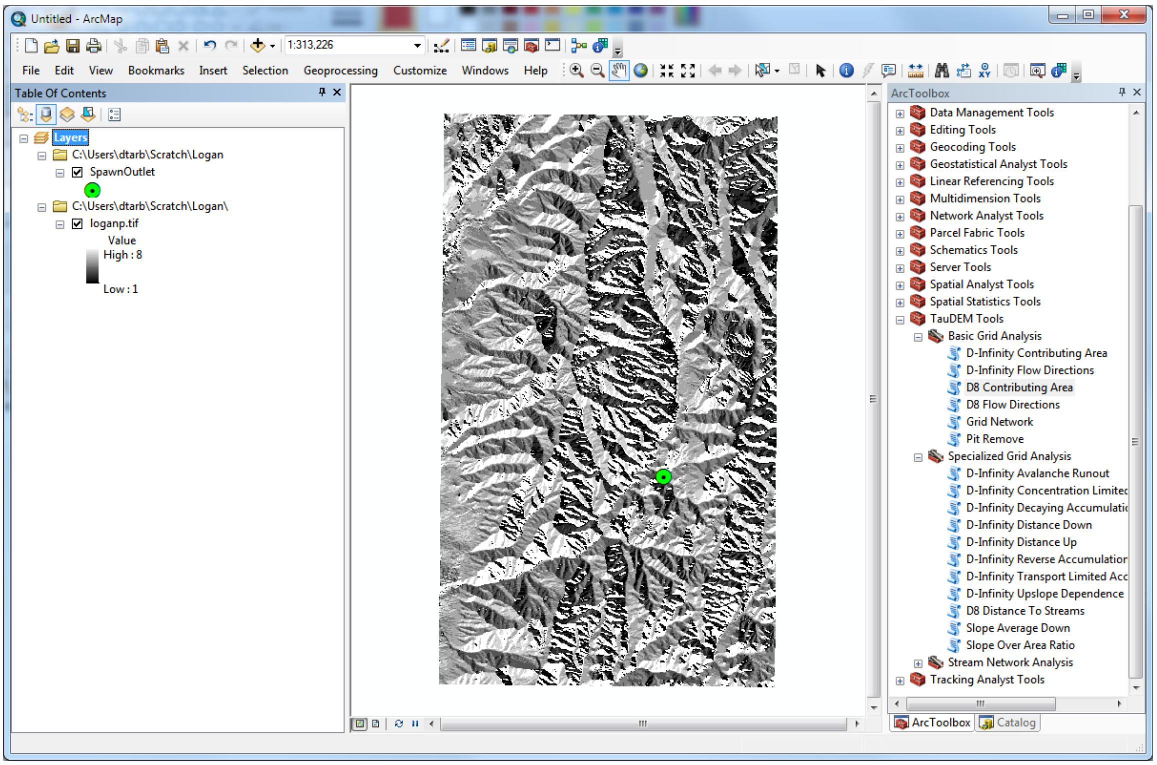
To turn in:

5. *Report the following for the Logan River*
    - *mean annual discharge in cfs*
    - *mean annual runoff (discharge per unit area) in mm*
    - *Minimum, maximum and mean of mean annual precipitation over the Logan River watershed from PRISM in mm*
    - *Runoff ratio for the Logan River*

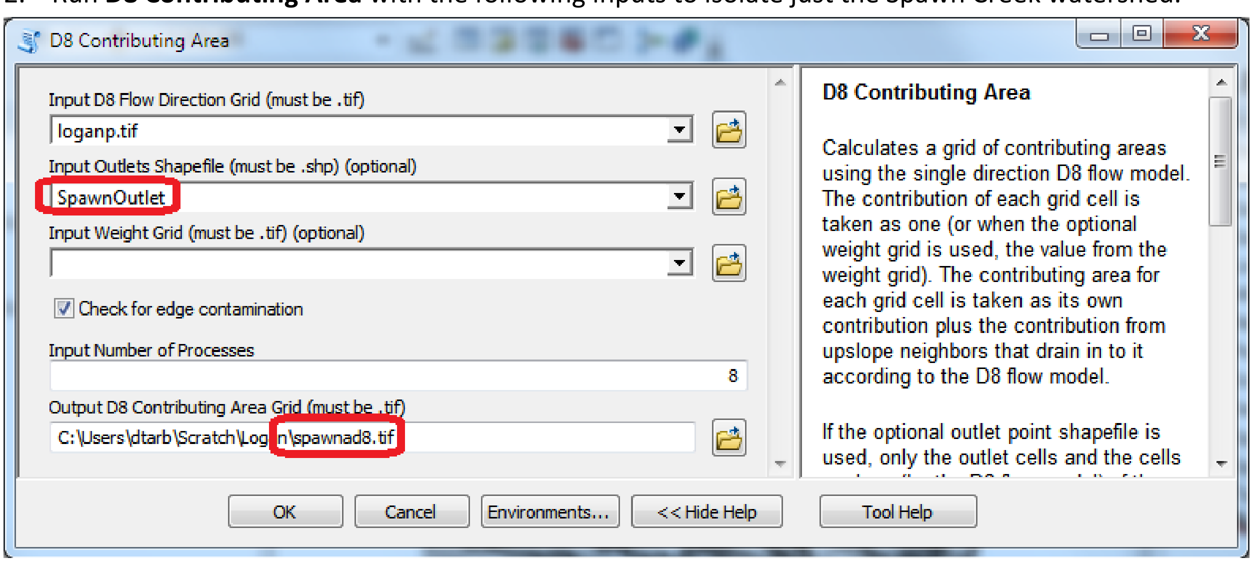
4. Spawn Creek TOPMODEL exercise

This exercise sets up the data and guides you through the calculations involved in the Spawn Creek TOPMODEL runoff generation calculation that is Example 4 in the Rainfall Runoff Processes Module (http://hydrology.usu.edu/rrp/Document/index.asp?Parent=19#). Spawn Creek is a tributary of the Logan River, so this exercise uses the same data as the Logan River Exercise above, which is more recent and at a higher resolution (10 m cell size) than the 30 m cell size data used in the online module.

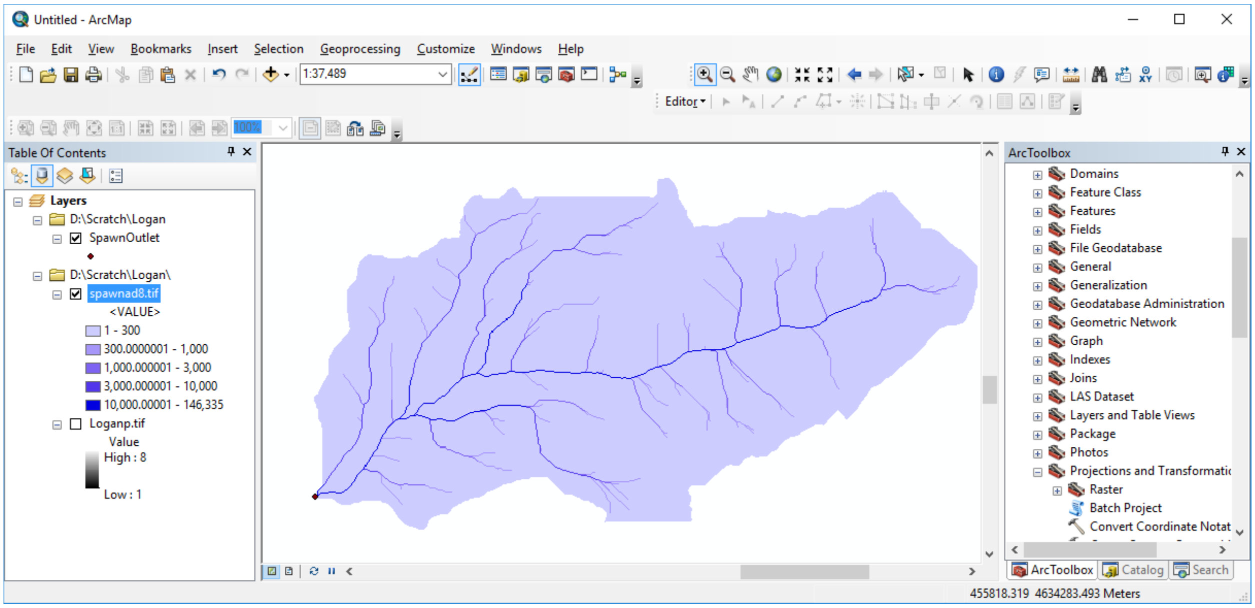
1. Open a new ArcMap document and load loganp.tif and spawnoutlet.shp.



2. Run **D8 Contributing Area** with the following inputs to isolate just the Spawn Creek watershed.

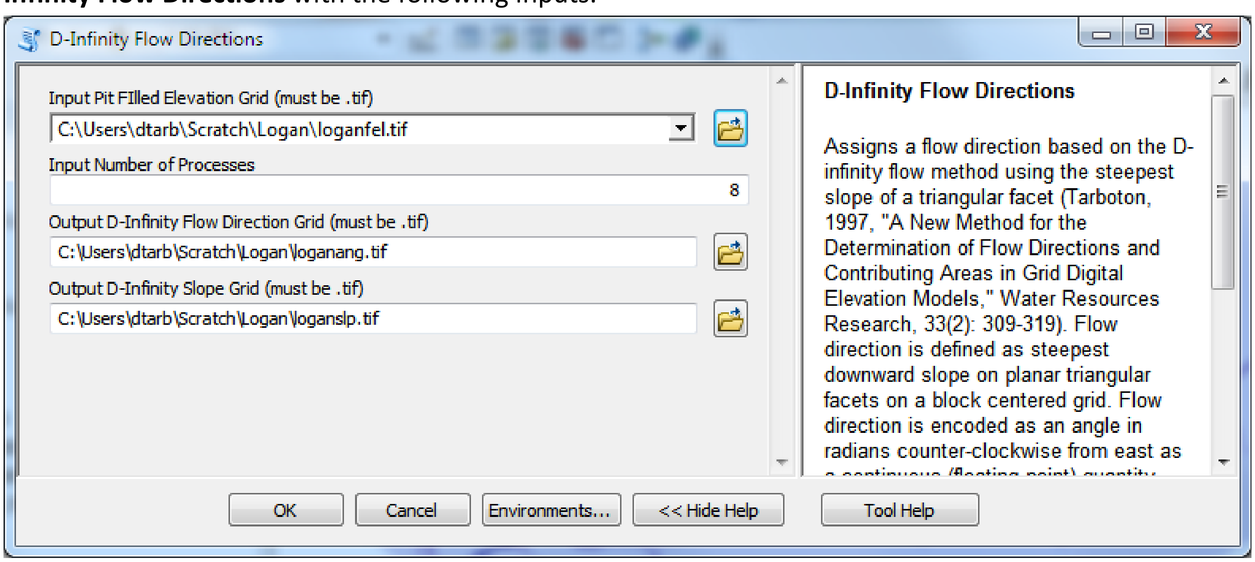


The result is illustrated below.

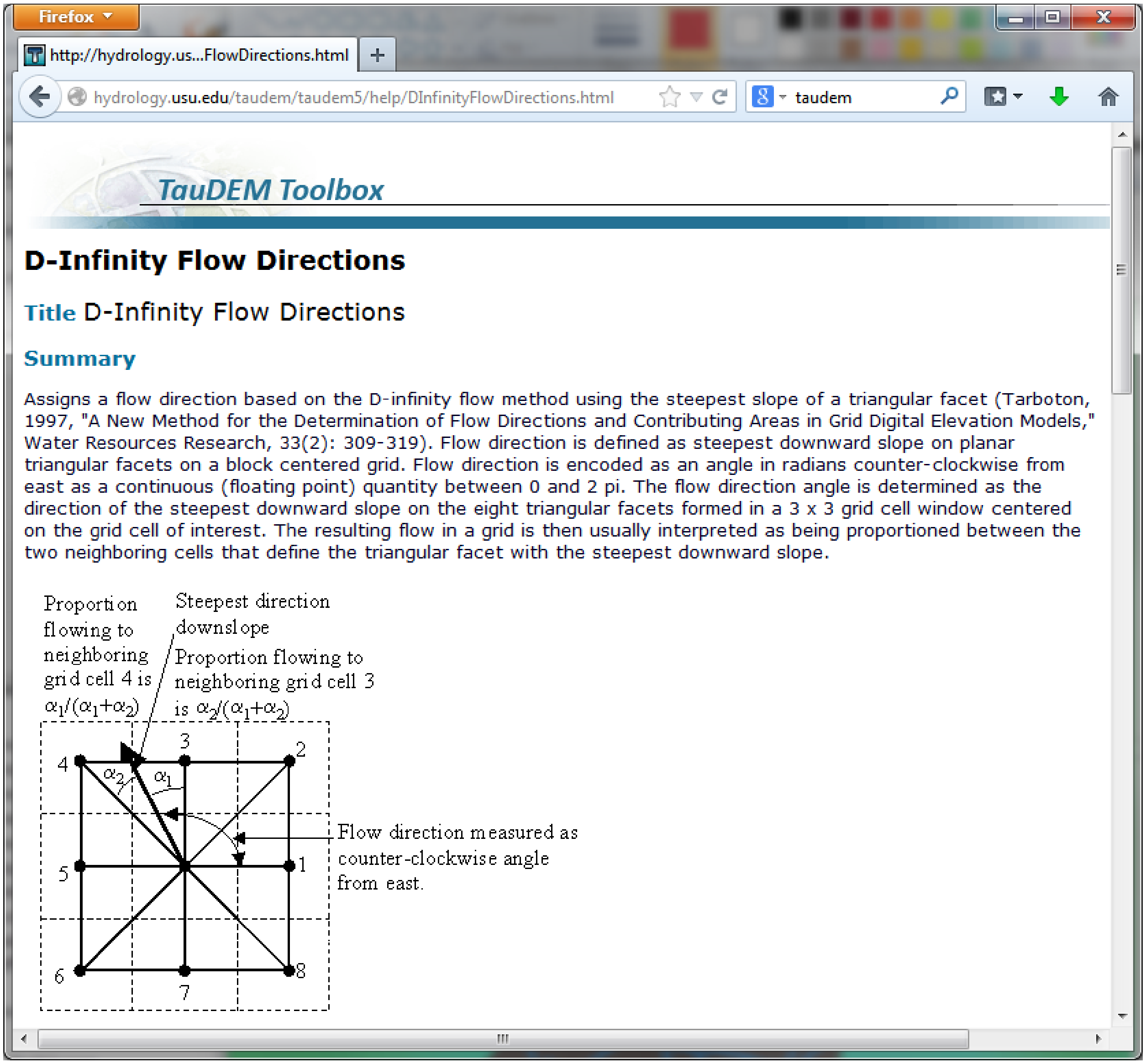


In all the work above the single flow direction model D8, was used, with flow being routed from each grid cell to only one neighbor. TauDEM also uses the D∞ (D-Infinity) flow model that calculates the steepest outwards flow direction using triangular facets centered on each grid cell and apportions flow between neighboring grid cells based on flow direction angles. This is useful for calculating specific catchment area used in TOPMODEL.

3. The **D-Infinity Flow Directions** function is starting point for all D-Infinity work. It calculates D-Infinity flow directions for use in other TauDEM functions requiring D-infinity flow direction input. Run **D-Infinity Flow Directions** with the following inputs.



D-Infinity flow directions are encoded as angles counter clockwise from East in Radians as illustrated in the help



http://hydrology.us...FlowDirections.html

hydrology.usu.edu/taudem/taudem5/help/DInfinityFlowDirections.html

TauDEM Toolbox

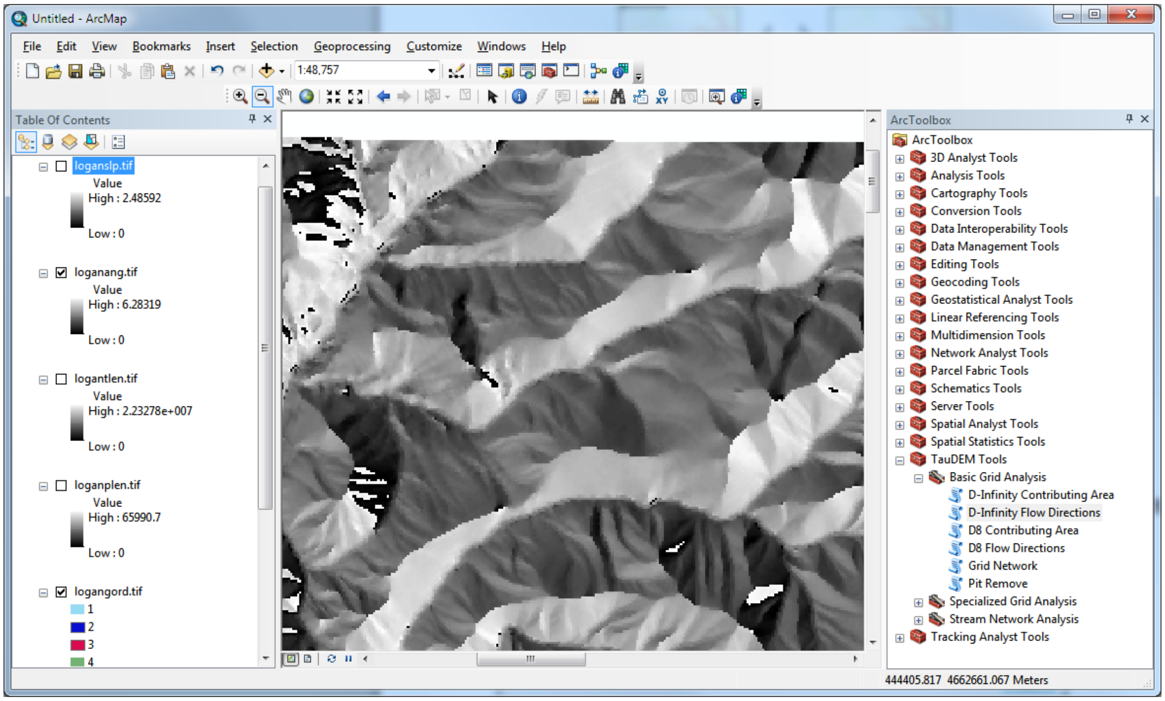
D-Infinity Flow Directions

Title D-Infinity Flow Directions

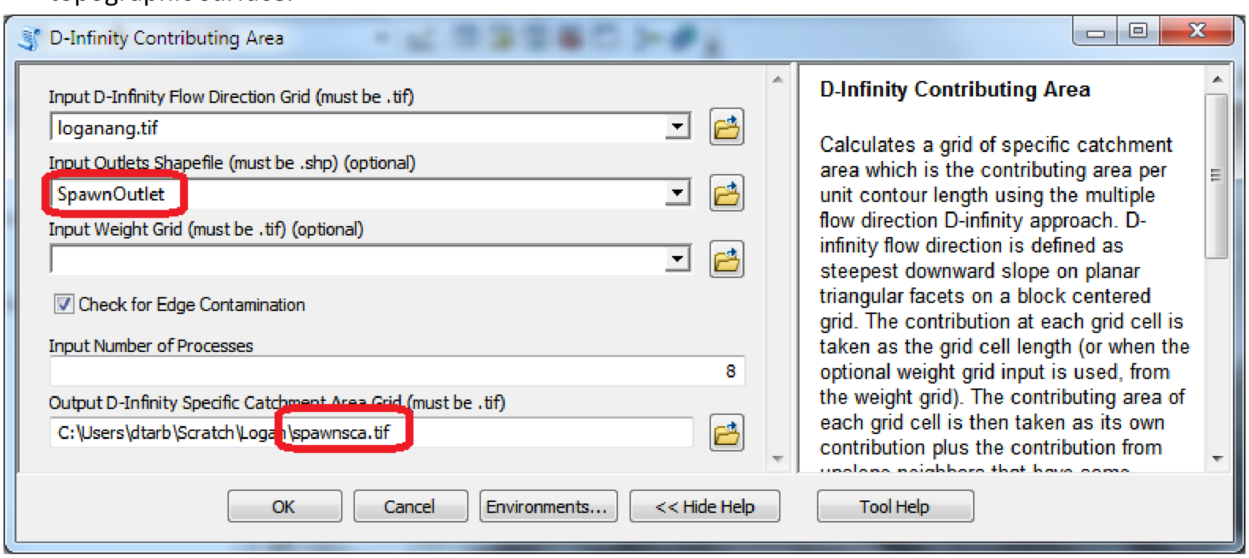
Summary

Assigns a flow direction based on the D-infinity flow method using the steepest slope of a triangular facet (Tarboton, 1997, "A New Method for the Determination of Flow Directions and Contributing Areas in Grid Digital Elevation Models," Water Resources Research, 33(2): 309-319). Flow direction is defined as steepest downward slope on planar triangular facets on a block centered grid. Flow direction is encoded as an angle in radians counter-clockwise from east as a continuous (floating point) quantity between 0 and 2 pi. The flow direction angle is determined as the direction of the steepest downward slope on the eight triangular facets formed in a 3 x 3 grid cell window centered on the grid cell of interest. The resulting flow in a grid is then usually interpreted as being proportioned between the two neighboring cells that define the triangular facet with the steepest downward slope.

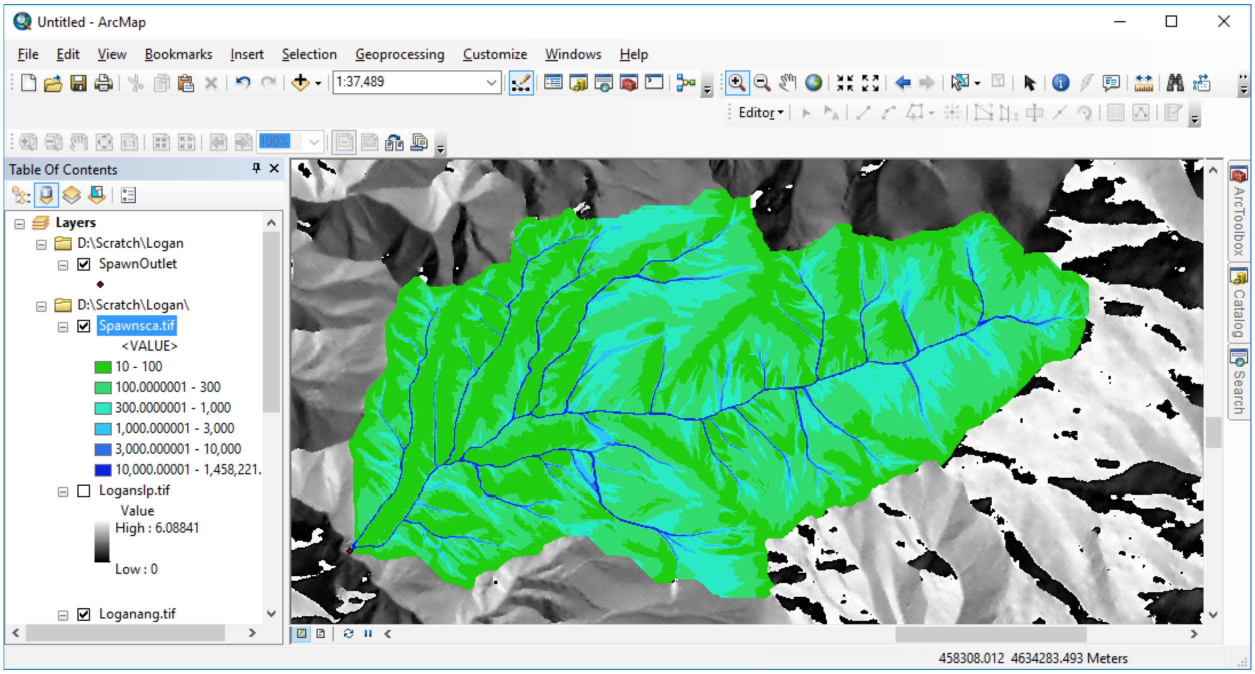
D-Infinity flow directions render similar to a hillshading



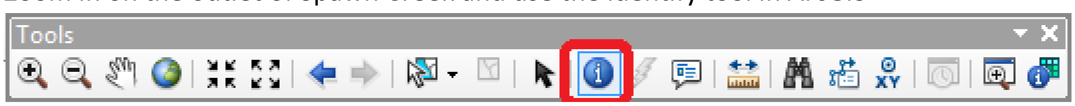
4. **The D-Infinity Contributing Area** function evaluates contributing area using the D-Infinity model based on flow being shared between grid cells proportional to the angle to the steepest downslope direction. This is designed to represent specific catchment area within dispersed flow over a smooth topographic surface.



The result is illustrated below



Zoom in on the outlet of Spawn Creek and use the identify tool in ArcGIS

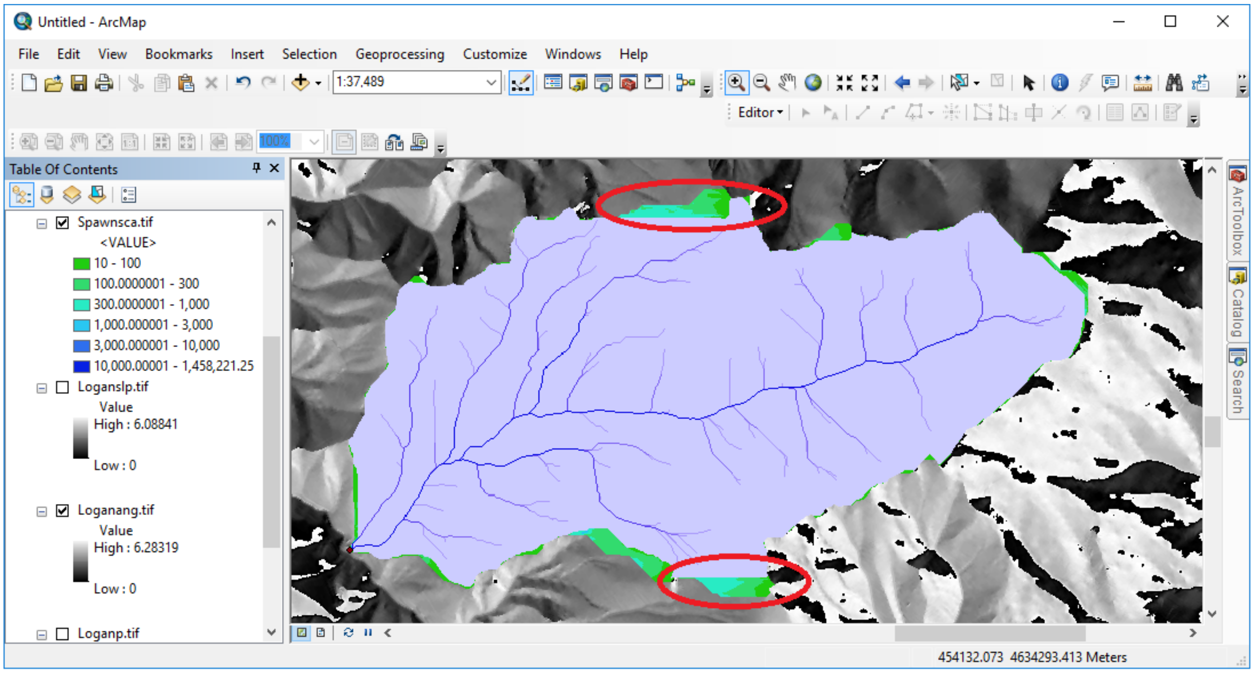


to identify the value of *spawnad8.tif* at the location of the outlet. Examine also the value of *spawnsca.tif* at this location. Examine the properties of *spawnsca.tif* and determine its cell size.

To turn in:

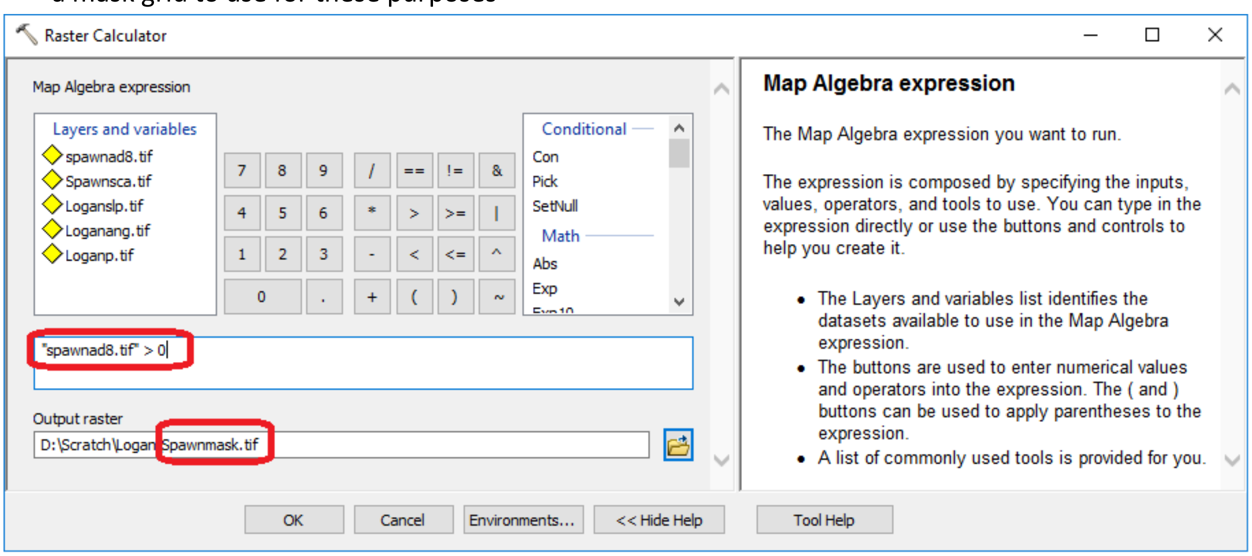
6. *Report the contributing area draining to the outlet location in number of cells and square kilometers. Report the area of a single grid cell.*
7. *Report the value of D-Infinity contributing area at this location. Reconcile and explain the values of D8 contributing are and D-Infinity contributing area in terms of grid cell size.*

If you examine spawnsca.tif carefully you will see that it has been evaluated over a larger domain than spawnad8.tif. This is most easily seen when you display spawnad8.tif above spawnsca.tif. In the below I have circled in red some of the differences.

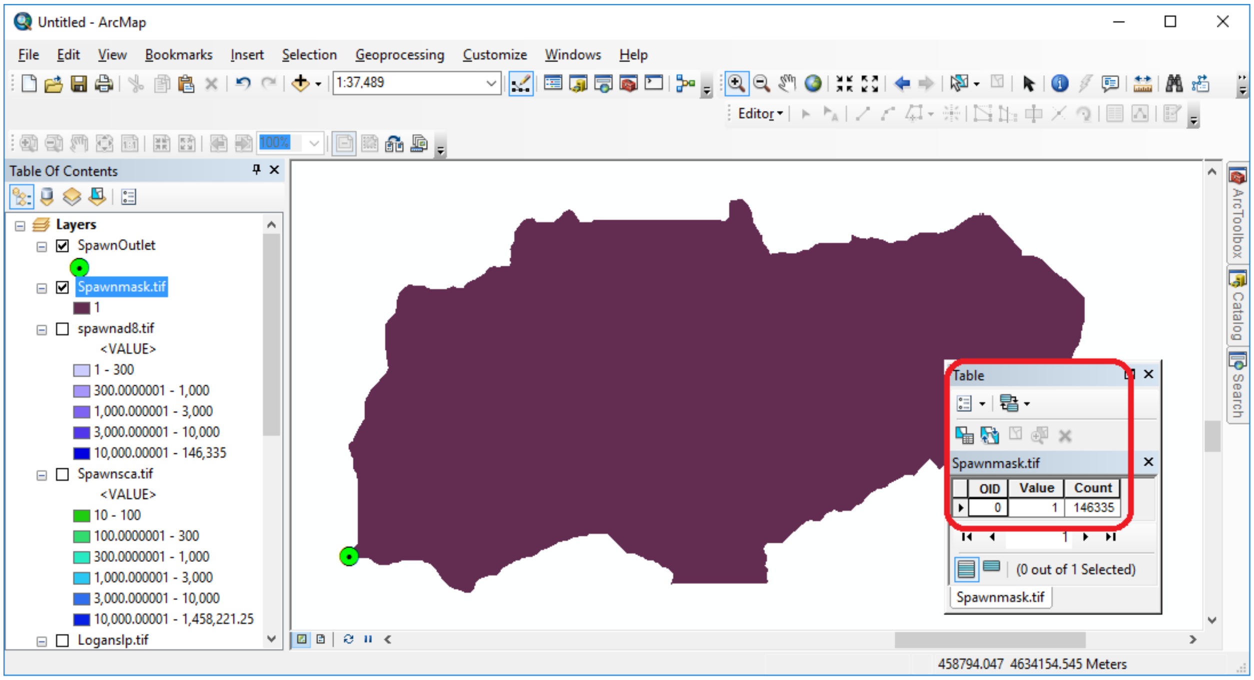


This is because the D-Infinity Contributing area function includes grid cells that only have part of their area draining to the outlet, while the D8-Contributing Area Function includes only cells that drain entirely to the outlet using the D8 model.

5. **D8 Contributing area Mask**. To retain consistency in the area used in the calculations we will mask our calculations using the D8 contributing area. The following Raster Calculator calculation results in a mask grid to use for these purposes



The result is illustrated below.



The attribute table of spawnmask.tif indicates that this area contains 146335 grid cells, an area of 14.6 km^2. These values are slightly different from the values in the module (Chapter 6:8) as we are using a higher resolution DEM more recently downloaded from the National Elevation Dataset. These sort of small differences are not unusual in DEM analyses repeated for the same area with different data. This exercise will follow Example 4 in the module but with the current DEM data.

Assume the following hydrologic and parameter inputs

K_o= 10 m/hr

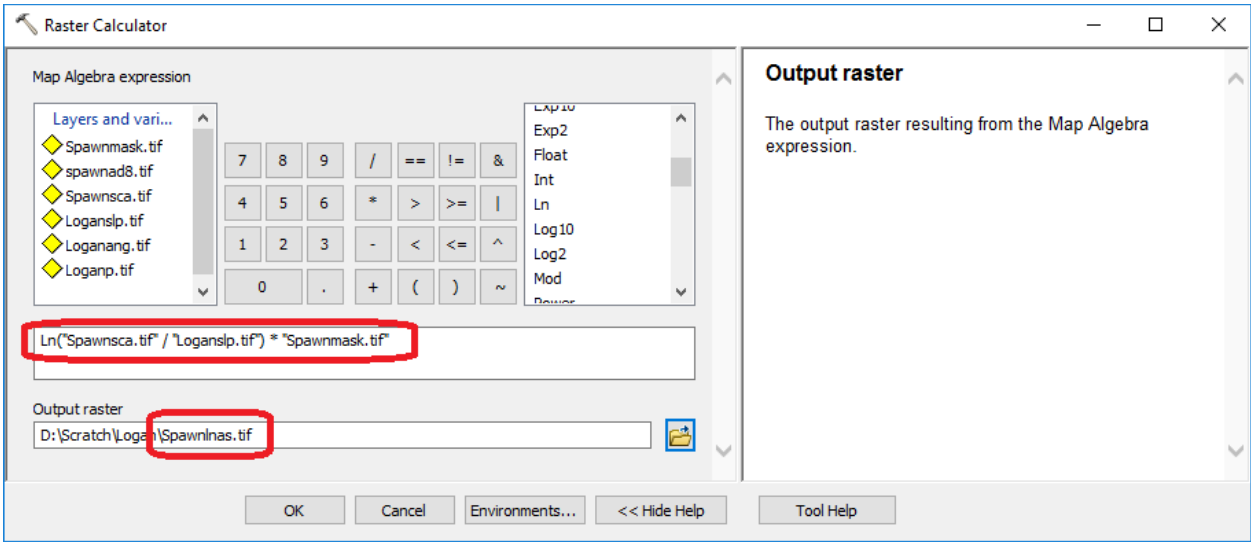
f= 5 m^{-1}

θ_e = 0.2

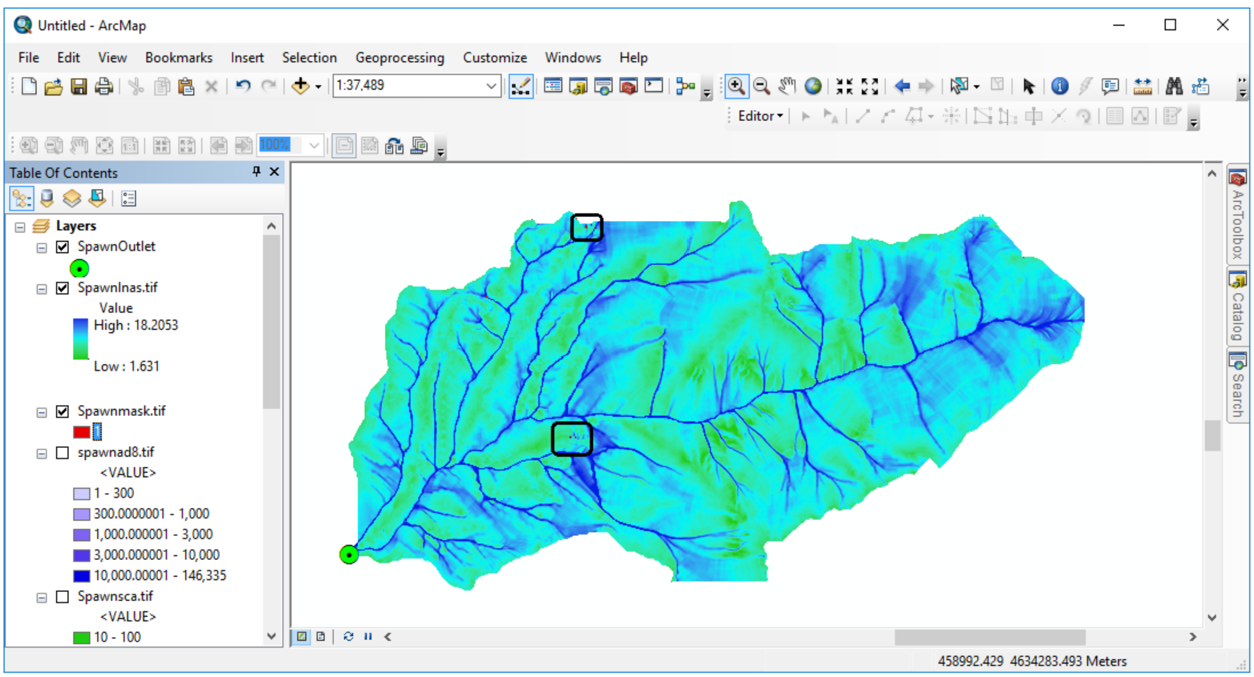
Q_b = 0.8 m^3/s

Assume that we want to calculate the runoff due to 25 mm or rainfall.

6. Use the following **raster calculation to evaluate wetness index**, ln (a/S).

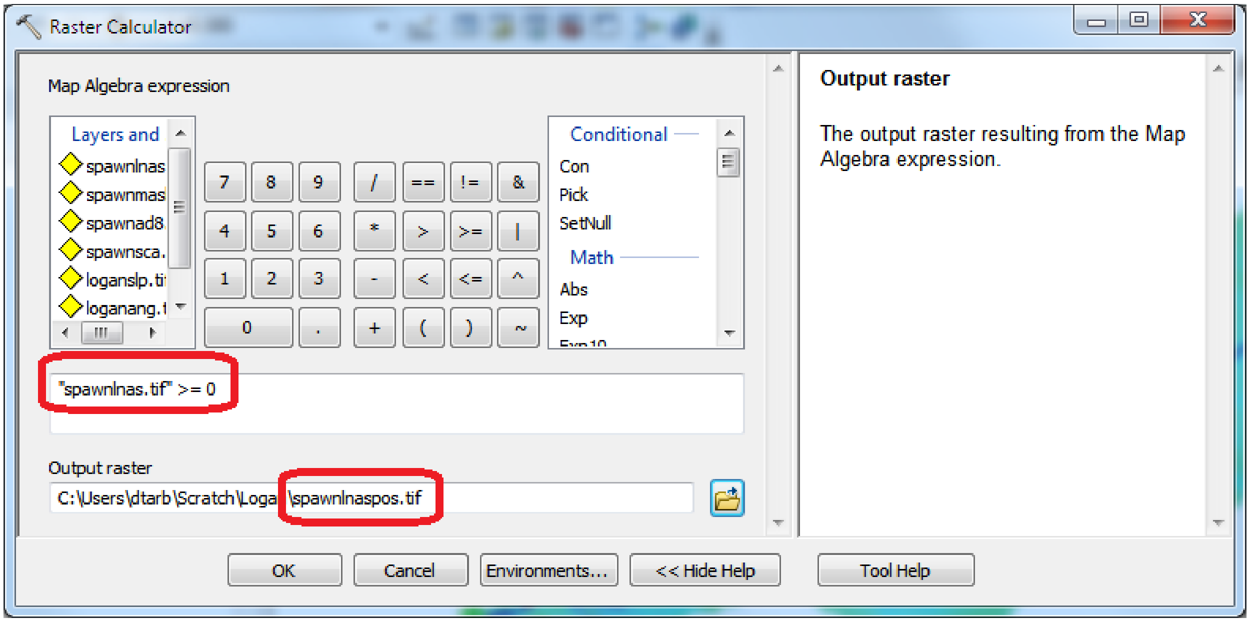


The result is:

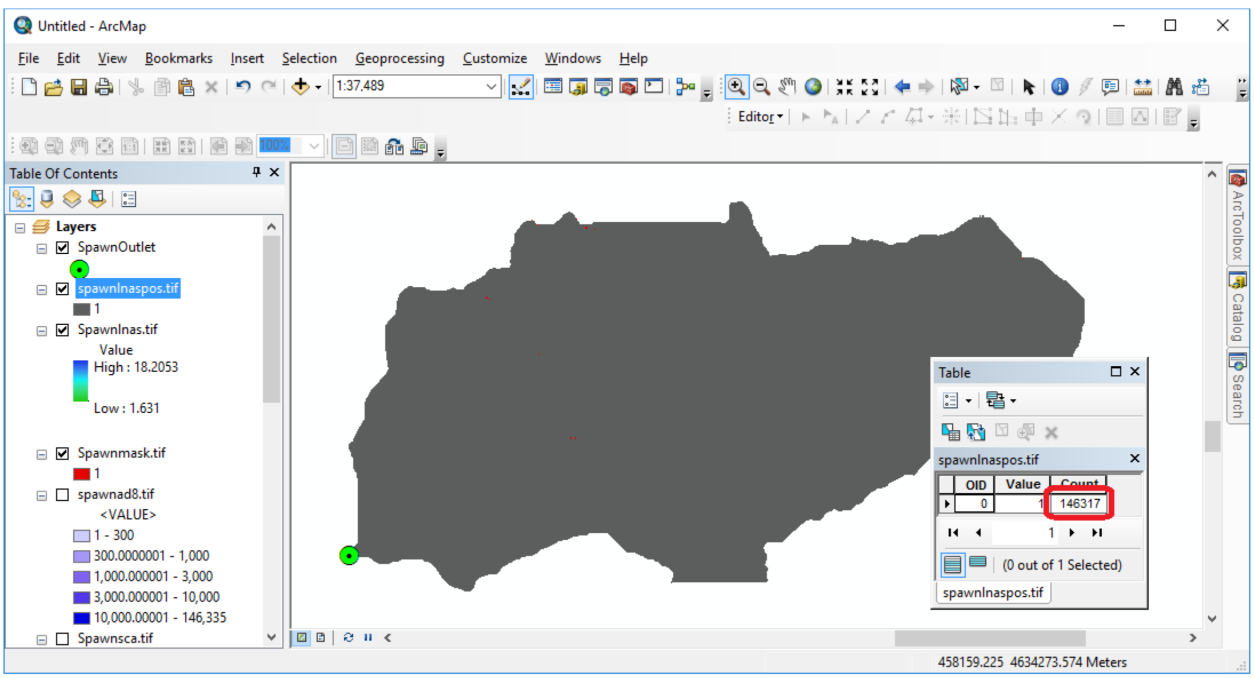


Note that in the calculation I used the multiply by the mask to isolate the result to the masked area. Note also that I changed the color used to symbolize the mask to red and have this turned on behind the wetness index layer, spawnlnas.tif. You can see red showing through in a few places. These are locations where the slope is 0 and ln(a/S) results in no-data.

The following raster calculation determines how many grid cells are like this.



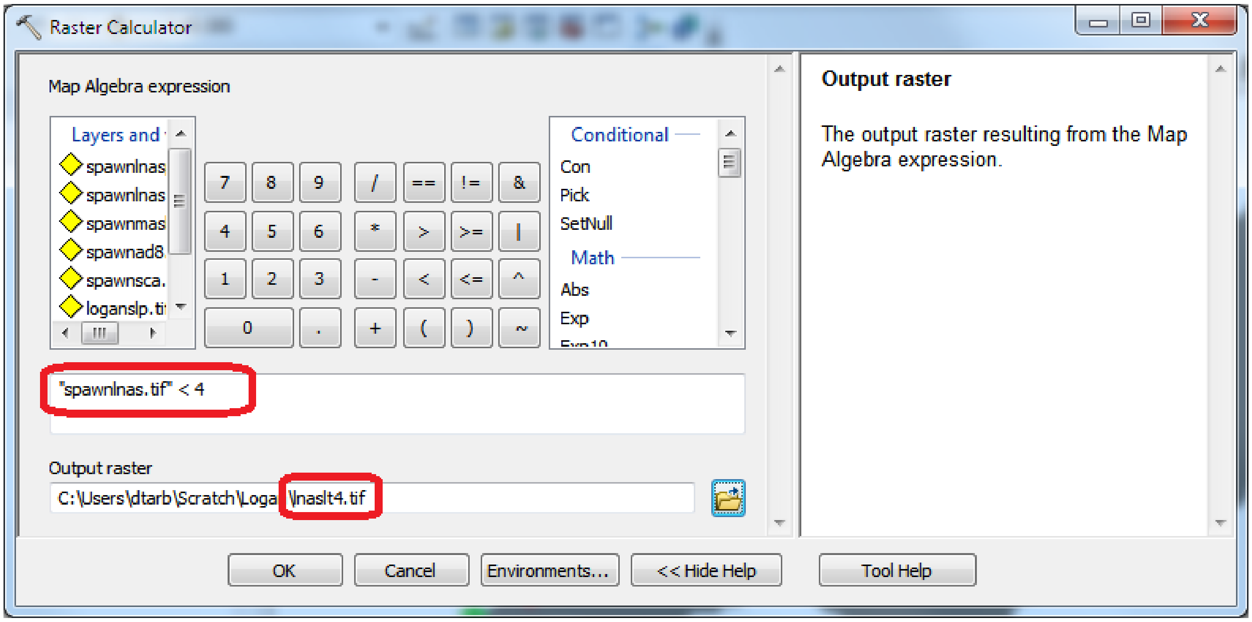
The result is



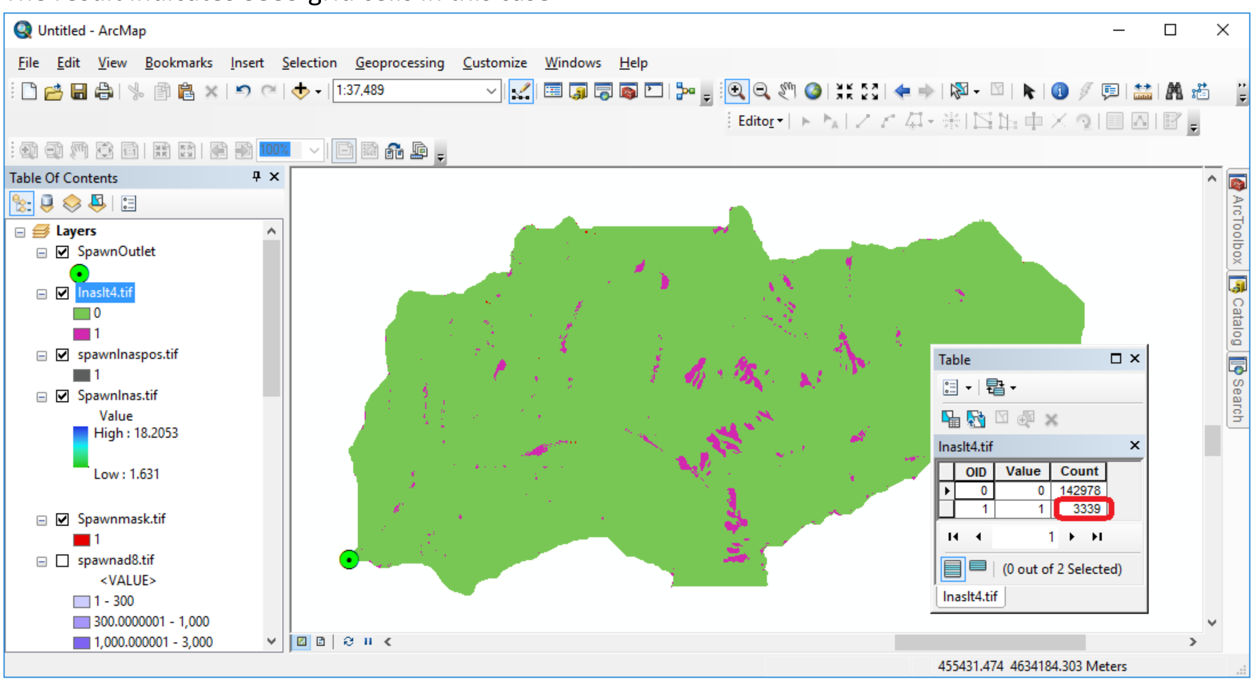
The attribute table of the result indicates 146317 positive grid cells so there are 146335-146317 = 18 grid cells with zero slope.

The properties of spawnlnas.tif indicate the average value that is $\bar{\lambda}$ in TOPMODEL theory.

7. **Evaluate wetness index distribution.** spawnlnas.tif may be used to evaluate the distribution of wetness index through a series of raster calculations. Select a manageable number of bin values (e.g. <4, 4-6, 6-8, 8-10, ... 18-20). The number of grid cells in each can be evaluated using a raster calculation such as



The result indicates 3339 grid cells in this case



Use a series of these calculations to evaluate and plot a histogram of ln(a/S) for Spawn Creek similar to the one in the Exercise on page 6:14 of the module.

To turn in:

8. A histogram of wetness index distribution ln(a/S) for Spawn Creek.

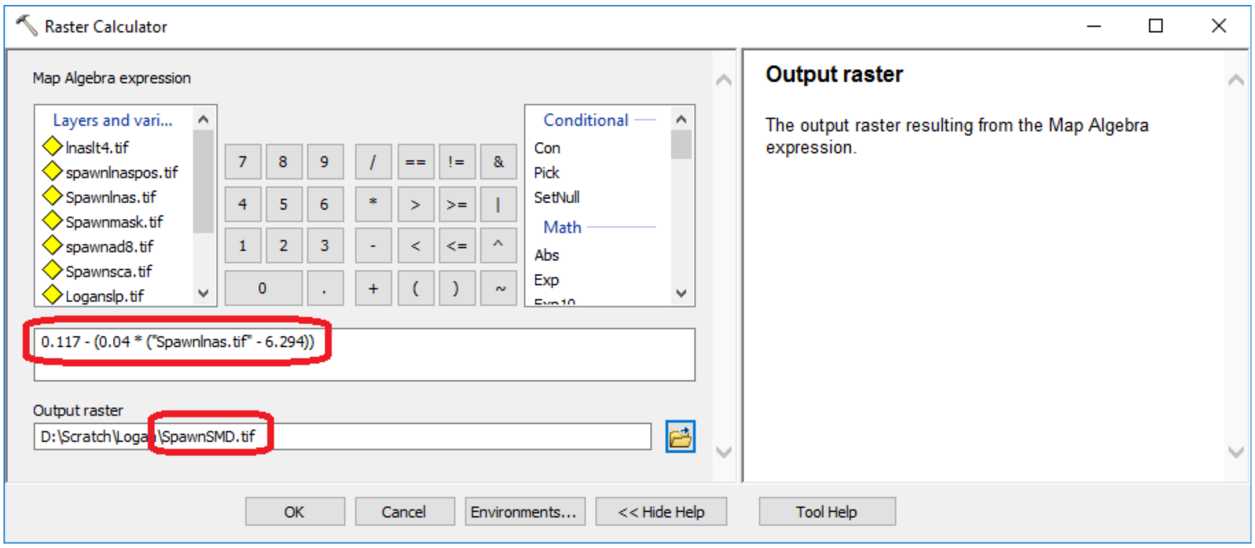
8. **Evaluate soil moisture deficit**. Evaluate $\overline{D}$ using equation (85) from the module

$$\overline{D} = -m\ln(r) + m\,\overline{\ln(T_o)} - m\overline{\lambda}$$

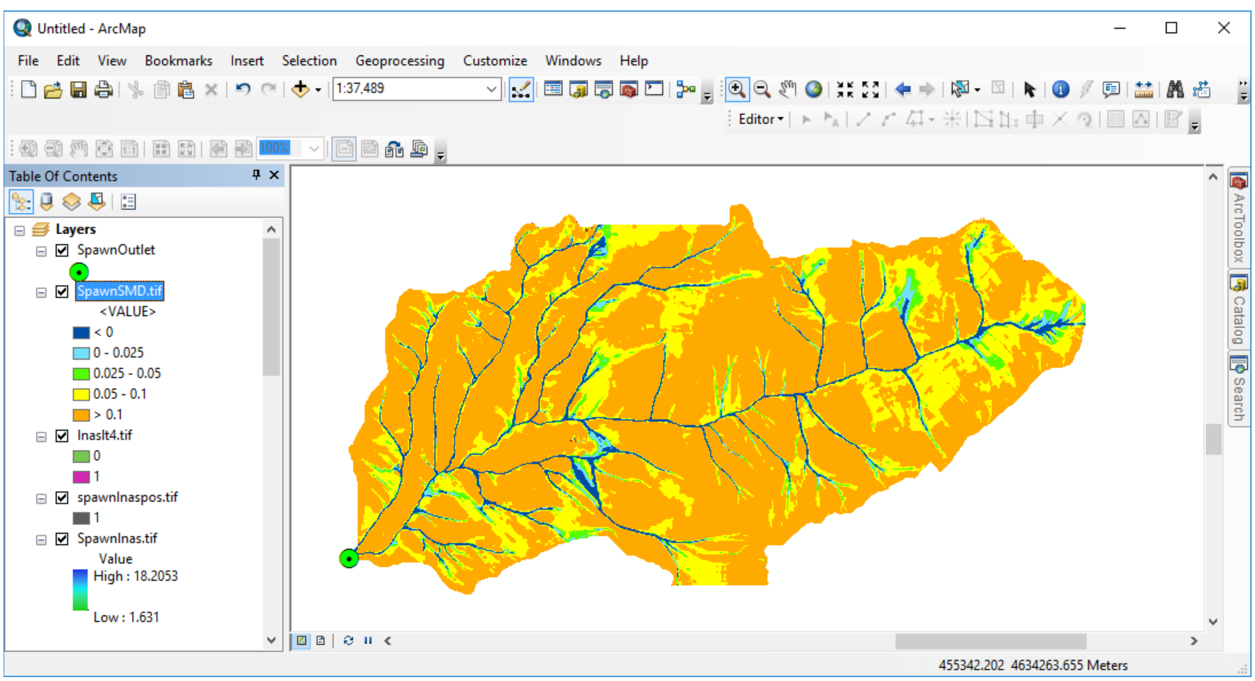
A raster calculation to evaluate soil moisture deficit D following equation (87) can then be set up:

$$D = \overline{D} - m\left(\ln(a/S) - \overline{\lambda}\right) = 0.117 - 0.04 \times (\ln(a/S) - 6.294)$$

Perform this calculation for your parameter values



The result shows soil moisture deficit



The dark blue grid cells are saturated. The light blue cells have soil moisture deficit less than 0.025 m so will saturate with 25 mm of infiltration. The remaining grid cells would not saturate and would not generate runoff during our 25 mm storm.

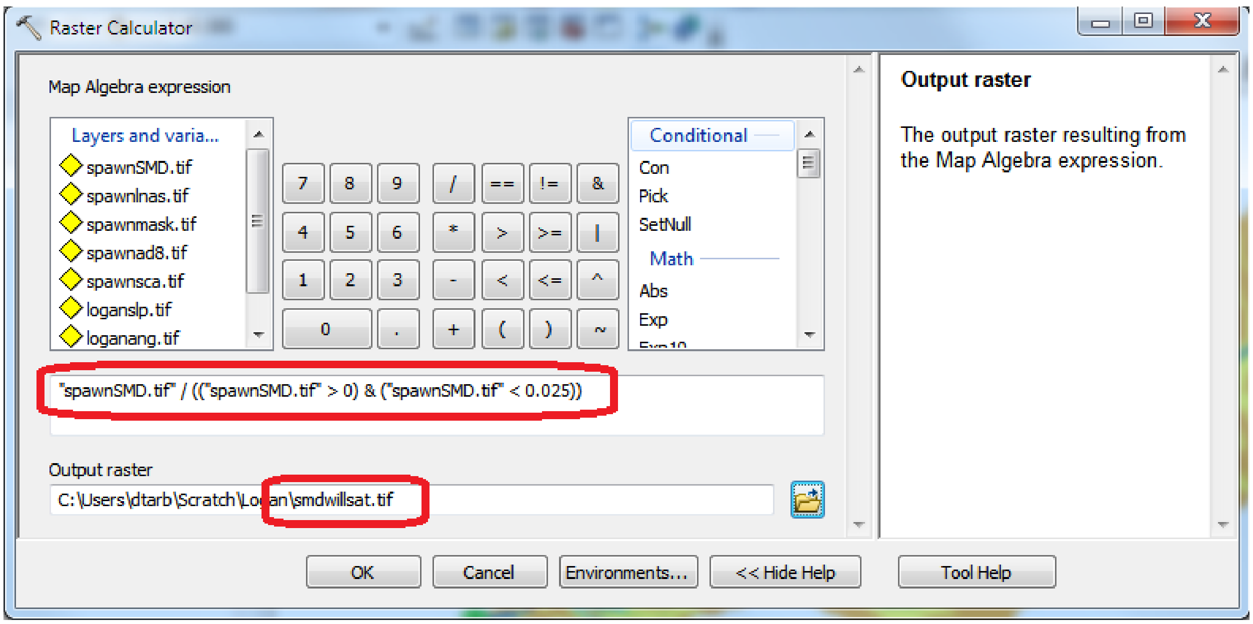
To turn in:

9. Report the value of the TOPMODEL parameters $\overline{\lambda}$ *and* $\overline{\mathrm{D}}$ *for Spawn Creek and the conditions given.*

10. A neatly labeled layout map showing the soil moisture deficit for these conditions.

A raster calculation can be used to determine the fraction of area that is saturated (D <= 0) which when combined with the flat area gives the area where there is no infiltration and all precipitation is runoff.

Similarly a raster calculation can be used to isolate the area with D between 0 and 0.025 m. This is the area that will saturate during the storm. This raster calculation requires a bit of conditional logic and is



Subtracting the average of smdwillsat.tif from 0.025 gives the average depth of runoff generated from this area, which when combined with the area gives the total runoff.

To turn in:

11. The area and volume of runoff generated from flat areas for these conditions

12. The area and volume of runoff generated from saturated areas for these condition

13. The area and volume of runoff generated from areas that will saturate for these conditions

14. The total volume and per unit area depth of runoff generated for these conditions

15. The runoff ratio from this storm with these conditions

Summary of Items to turn in.

1. *Report the contributing area draining to the outlet location in number of cells, square kilometers and square miles. Report the area of a single grid cell. Compare your result in square miles to the USGS drainage area value for this site.*
2. *Prepare a table that reports for the 9 stream links in the Spawn Creek tributary of the stream network the following attributes:*
    - *Link number*
    - *Downstream link number*
    - *Upstream link number 1*
    - *Upstream link number 2*
    - *Downstream contributing area*
    - *Length*
    - *Identifier of corresponding watershed (WSNO)*
3. *Open the attribute table of loganw and identify the count (number of grid cells) of the 9 Spawn Creek subwatersheds. Based on this count calculate area of each subwatershed and reconcile your values with contributing area values in the table from the stream network.*
4. *Prepare a diagram that shows, based on your answers to 2 and 3, how connectivity between subwatersheds, stream links and upstream and downstream links is encoded.*
5. *Report the following for the Logan River*
    - *mean annual discharge in cfs*
    - *mean annual runoff (discharge per unit area) in mm*
    - *Minimum, maximum and mean of mean annual precipitation over the Logan River watershed from PRISM in mm*
    - *Runoff ratio for the Logan River*
6. *Report the contributing area draining to the outlet location in number of cells and square kilometers. Report the area of a single grid cell.*
7. *Report the value of D-Infinity contributing area at this location. Reconcile and explain the values of D8 contributing are and D-Infinity contributing area in terms of grid cell size.*
8. *A histogram of wetness index distribution ln(a/S) for Spawn Creek.*
9. *Report the value of the TOPMODEL parameters* $\overline{\lambda}$ *and* $\overline{\mathrm{D}}$ *for Spawn Creek and the conditions given.*
10. *A neatly labeled layout map showing the soil moisture deficit for these conditions.*
11. *The area and volume of runoff generated from flat areas for these conditions*
12. *The area and volume of runoff generated from saturated areas for these condition*
13. *The area and volume of runoff generated from areas that will saturate for these conditions*
14. *The total volume and per unit area depth of runoff generated for these conditions*
15. *The runoff ratio from this storm with these conditions.*