Lab 2: Watershed Derived Data

Topics Covered in this Lab:

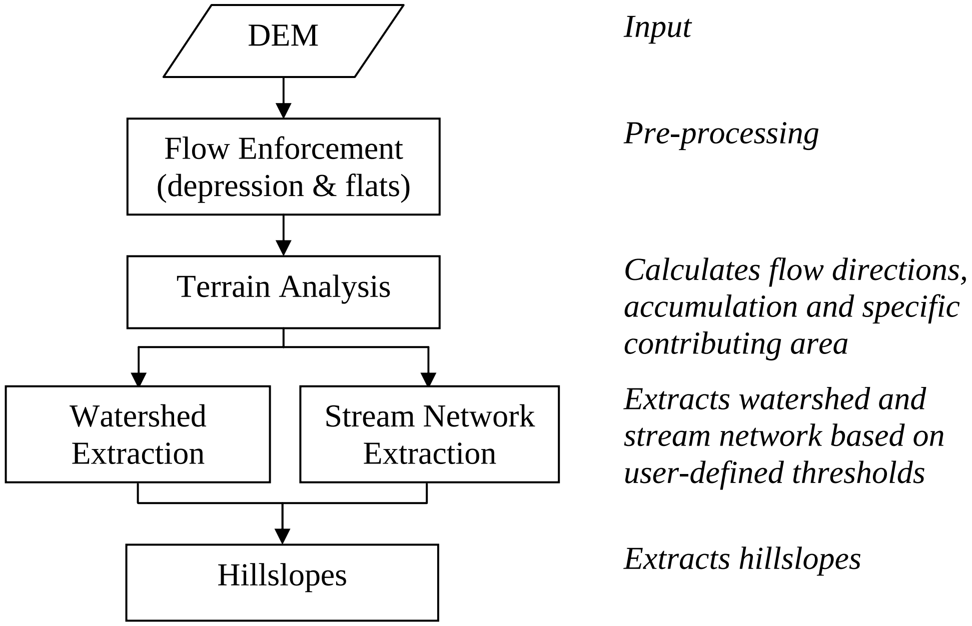
i. DEM pre-processing
ii. Derivatives of the flow network: the flow routing concept
iii. Extracting stream networks from the flow network
iv. Extracting watersheds
v. Extracting hillslopes

Take Home from Lab 2:

After completing this lab you should be familiar with the concepts and techniques involved in the extraction of stream networks and watersheds.

Introduction:

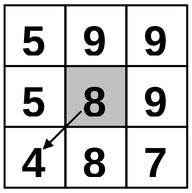
Among of the most common uses of DEMs is the automated delineation of stream networks and watersheds. These features are fundamental units for environmental modeling and management because they partition landscapes in a way that is relevant to the geomorphic and hydrological processes operating in an area. The stream network, for example, is the boundary between the concentrated processes acting in channels (e.g. channel incision) and the diffusive processes acting on the surrounding hillslopes (e.g. wash flow). From a hydrological point of view, precipitation falling on either side of a watershed divide will follow different flowpaths, with potential implications for water quality. Therefore, an understanding of the theoretical and technical aspects of stream network and watershed extraction is important. In this lab, you will follow the process involved in automated stream network and watershed extraction described in the following flow diagram.



i. DEM Pre-processing: Flow Enforcement

The Flow-Routing Concept:

Overland and near-surface water flow can be modeled using DEMs if we assume that surface topography is the sole factor in the distribution of water. One very simple model routes all water from a particular grid cell in a DEM to a single neighbouring cell (i.e., water is not partitioned between multiple neighbours). This ‘D8’ (8 direction) method sets the flow direction toward the lowest of the eight neighbouring cells, in relation to the centre cell. Therefore, flow is allowed in one of eight possible directions, assuming that water will travel along the steepest downslope path. Based on the 3x3 cell neighbourhood to the right, flow would be directed from the centre cell (elevation of 8) to the southwest cell (elevation of 4).



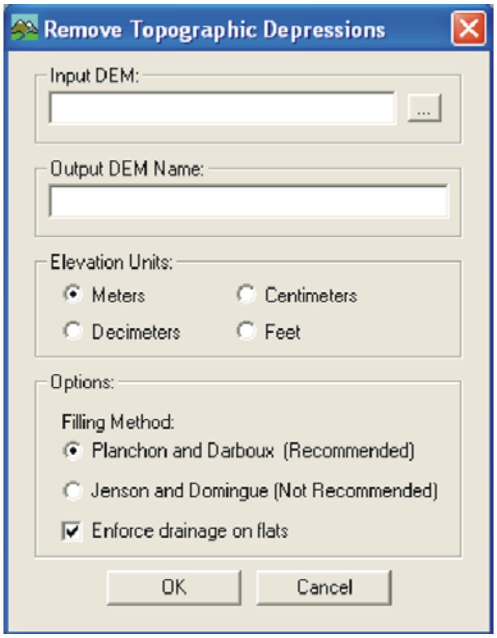
5	9	9
5	8	9
4	8	7

Interuptions to Flow Routing:

Flow direction is undefined when a grid cell, or group of grid cells, is lower than all neighbouring cells. In essence, all water that enters a cell with no downslope neighbour is unable to get out and becomes stuck. We refer to these features as pits if they are a single cell in size, and depressions if they consist of groups of cells. Often, these features are artifacts of the data and should be removed during DEM pre-processing. Pre-processing involves altering the elevations of a DEM in a way that enforces continous flow-paths. It is important to realize that sometimes these ‘digital depressions’ reflect actual features in the landscape, and should be preserved during flow modelling. However, for our work, we will assume that all depressions in DEMs are artifacts and are justified in being removed.

Several methods have been developed for removing depressions from DEMs. These methods vary greatly in terms of their sophistication and impact on the DEM. The two most common depression-removal methods are depression filling and depression breaching. Depression filling raises cells within a depression to the elevation of the outlet cell (i.e. the lowest cell on the depressions catchment). Depression breaching digs a trench from a depression’s bottom to some point downslope.

Not all interuptions to flow routing are caused by depression cells. Often, DEMs contain extensive flat regions (areas of equal elevation). Flat areas interupt flow routing in the same way as depressions. Cells within a flat region do not have downslope neighbours, and therefore, flow routing is impossible on flat sites without pre-processing. Correction of flow direction on flat sites typically involves finding an outlet cell, forcing flow from cells adjacent to the outlet to the outlet, and continuing backwards in an interative manner (e.g., Jenson and Dominique, 1988).



Remove Topographic Depressions

Input DEM:

Output DEM Name:

Elevation Units: ● Meters ○ Centimeters ○ Decimeters ○ Feet

Options:

Filling Method: ● Planchon and Darboux (Recommended) ○ Jenson and Domingue (Not Recommended)

☑ Enforce drainage on flats

1. In TAS, click *Pre-processing menu* ➔ *Remove Depressions sub-menu* ➔ *Fill All Depressions*
2. Select 'Vermont' as your input DEM and call your output file 'Vermont Filled'. Elevations are in meters. Choose the default depression filling method (i.e. Planchon and Darboux) and keep the 'enforce drainage on flats' check box checked.
3. Press OK. The program will take approximately 10 passes to complete. The resulting DEM will have filled depression and fixed flats.
4. For comparison, we will also use the *Breach All Depressions* sub-program to remove depressions and correct flat areas in the 'Vermont' DEM. Choose 'Enforce Drainage on Flats'. Call the output file 'Vermont Breached'.
5. Use the *Raster calculator* (in the *GIS* Analysis menu or use the icon) to find which cells were impacted by depression filling and breaching. Use the following equations to identify grid cells that were altered:

Output Name	**Expression**
Fill Impact	'Vermont Filled'<>'Vermont'
Breach Impact	'Vermont Breached'<>'Vermont'

Notes: 1. <> is 'not equal to' 2. Images in the expression must be in apostrophes.

Q1. Compare the impacts of depression filling and depression breaching. (1 mark)

Q2. Open 'Vermont' using the atlas_relief palette and check the Hillshading option on the image attributes toolbar. Again, select 'Vermont' as the DEM for Hillshading Base. Also display 'Fill Impact' and 'Breach Impact' using the BW palette. Comment on the spatial distribution of depression cells. Why do you think this pattern occurs? (3 marks)

ii. Terrain Analysis: Calculating Flow Parameters

Now that we have a DEM that has had all interruptions to flow removed, we can continue to calculate the parameters needed to define the flow network, i.e. the topological network describing how each cell in a DEM is connected to all others. The sub-program used to derive these data is called *Flow Routing Algorithms* and can be reached by pressing the icon. First, a little background on flow routing data…

Pointers: the pointer data layer stores the flow direction of each cell in a raster grid, and thus, the topology of the flow network. The exact form of these data depends on the method used to derive the flow directions. TAS stores D8 pointers as binary numbers such that:

NW	N	NE
W		E
SW	S	SE

=

2^6	2^7	2^0
2^5		2^1
2^4	2^3	2^2

=

64	128	1
32		2
16	8	4

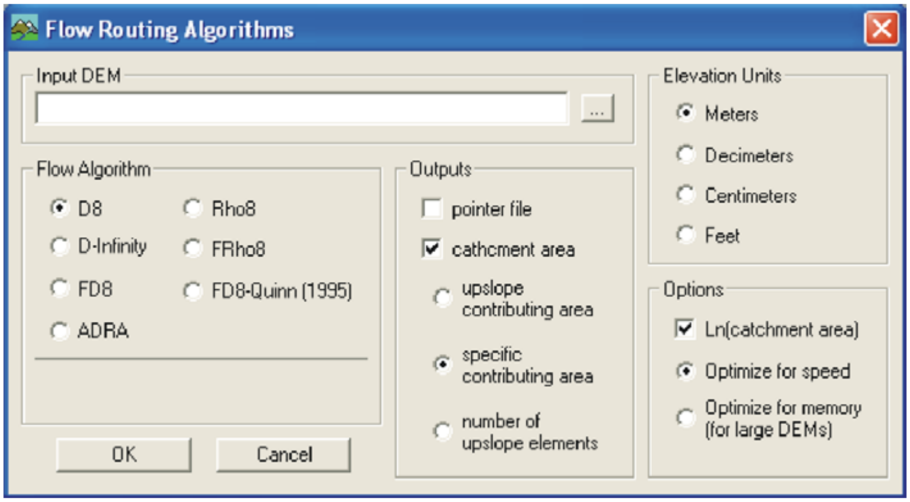
Several sub-programs in TAS use pointer file to calculate other terrain data, including the algorithms used to calculate catchment area (see below). However these sub-programs rarely require a pointer file as input, as TAS will automatically generate a pointer layer from the input DEM when required and then discard the file afterwards. Although this processing step is not readily apparent to the user, it is important to realize that it occurs. For example, when you run the *Watershed* sub-program, TAS takes the input DEM generates a D8 pointer layer, performs a watershed analysis and then discards the pointer file. If for some reason the user requires a pointer file for later analysis, it is also possible to generate and save pointer files using the *Flow Routing Algorithms* sub-program.

Catchment Area: These data describe the spatial pattern of upslope area draining to each pixel in a DEM. Measures of catchment area are often used for stream network extraction and other terrain indices. There are three measures of catchment area, each of which can be specified as output from the *Flow Routing Algorithms*. These measures include:

1. Number of Upslope Elements (NUE): the number of cells draining to each grid cell;
2. Upslope Contributing Area (UCA): the NUE multiplied by the cell area;
3. Specific Contributing Area (SCA): the UCA divided by the cell size or grid resolution.

The SCA characterizes the amount of flow across a unit length of contour in the catchment. Unlike the NUE and UCA, SCA is not affected by the grid resolution of the DEM.

1. Launch the *Flow Routing Algorithms* sub-program by pressing the icon or click: *Terrain Analysis* menu ➔ *Primary Terrain Attributes* sub-menu ➔ *Extended Neighbourhoods* sub-menu ➔ *Catchment Area*.



● D8
○ Rho8
○ D-Infinity
○ FRho8
○ FD8
○ FD8-Quinn (1995)
○ ADRA

☐ pointer file
☑ catchment area
○ upslope contributing area
● specific contributing area
○ number of upslope elements

● Meters
○ Decimeters
○ Centimeters
○ Feet

☑ Ln(catchment area)
● Optimize for speed
○ Optimize for memory (for large DEMs)

2. Specify ‘Vermont Breached’ as your input image. We will choose the D8 flow algorithm to create an SCA layer. You will use other types of flow algorithms in a future lab. The elevation units of this DEM are in meters. We will optimize for speed because the DEM is relatively small. When a DEM is very large (e.g., > 1000 x 1000 rows and columns) you may need to optimize for memory or an error will occur in running the program. Check the Ln(catchment area) option. This will produce a layer where each grid cell is the natural logarithm of the SCA. This is done because taking the natural logarithm can help displaying SCA data in a way that is more easily visually interpreted. SCA data have a very large range of values when not log-transformed.
3. You do not need to specify an output name because TAS will automatically assign one based on the input DEM name. Press OK to run the program.
4. TAS will create a new file called ‘Vermont Breached_D8_SCA’ when it has completed. Display this image using the ‘blueyellow’ palette and the DEM, ‘Vermont Breached’, in the *atlas_relief* palette (check Hillshading on the Image Attributes toolbar).
5. Zoom into the SCA image and move around to get an appreciation for the distribution of values.

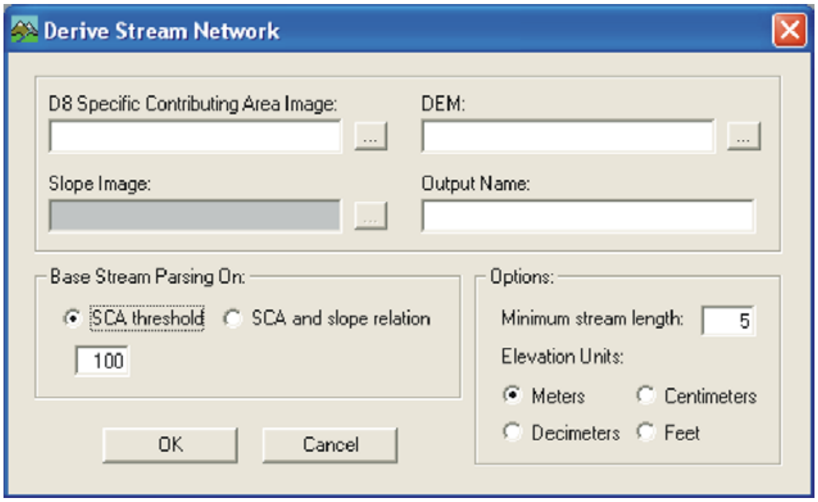
Q3. What parts of the landscape have low values of SCA? Which locations have high values of SCA? Why do you think that this is the case? (4 marks)

Q4. Knowing that a DEM is in UTM coordinates (i.e., measured in meters), what are the units of NUE, UCA, and SCA data layers? (3 marks)

iii. Extracting Stream Networks

There are several ways to extract a stream network from a DEM but the simplest method is to apply a threshold to the SCA data layer. Imagine for a moment that it is raining over a landscape and that as the precipitation hits the ground it travel overland based on our derived flow network. Locations with higher SCA values will have larger catchment areas, will capture more flow, and therefore, will have higher discharges. At some point downslope of the catchment divide the discharge will be high enough to cause surface erosion. Diffusive processes, like mass wasting and surface wash, tend to fill these incised areas back in. However, at some point the erosion will be so great that the incisive processes outweigh the effects of mass wasting and a stable channel head occurs over the long term. This is implies that there is a constant ‘critical support area’ for channels that mark the extent of the stream network. Let’s see how this works.

1. Although it is useful to log-transform SCA data for visualization, most sub-programs in TAS require the SCA layer in raw form. Re-calculate the ‘Vermont Breached_SCA’ image, this time without checking the Ln(catchment area) check box. TAS will automatically write overtop of your previous SCA image. Display the new image and examine the differences.
2. Click *Terrain Analysis* menu ➔ *Stream Network Analysis* sub-menu ➔ *Derive Network*. The *Derive Network* sub-program is launched.



● SCA threshold ○ SCA and slope relation

100

Minimum stream length: 5

● Meters ○ Centimeters

○ Decimeters ○ Feet

3. Select the image ‘Vermont Breached_SCA’ as your input D8 SCA layer and ‘Vermont Breached’ as your input DEM. Call the output image ‘Vermont Streams’.
4. Picking an appropriate value for the SCA threshold can be a difficult task. It requires that you preview the SCA layer and make a judgement about the extent of the stream network. This may be a ‘trial and error’ process, and may include comparison with

aerial photography or ‘blue-line’ streams from topographic maps. It will be different for every DEM. For now, use 50000 as the SCA threshold value.

5. The minimum stream length is the shortest stream allowed in grid cells. TAS will automatically erase any streams that have a stream length that is less than the specified value. This ‘stream pruning’ is purely for cartographic reasons. That is, typically we are not interested in having many very short streams in our derived network. Keep the default of 5 grid cells and press OK.
6. Open ‘Vermont Streams’ using the ‘BW’ palette. Zoom into the image to confirm that there are no breaks in the streams.

Note: If you wanted to create a vector equivalent of the streams file to overlay on the DEM you would use the *Convert Streams to Vector* sub-program in the *Stream Network* sub-menu.

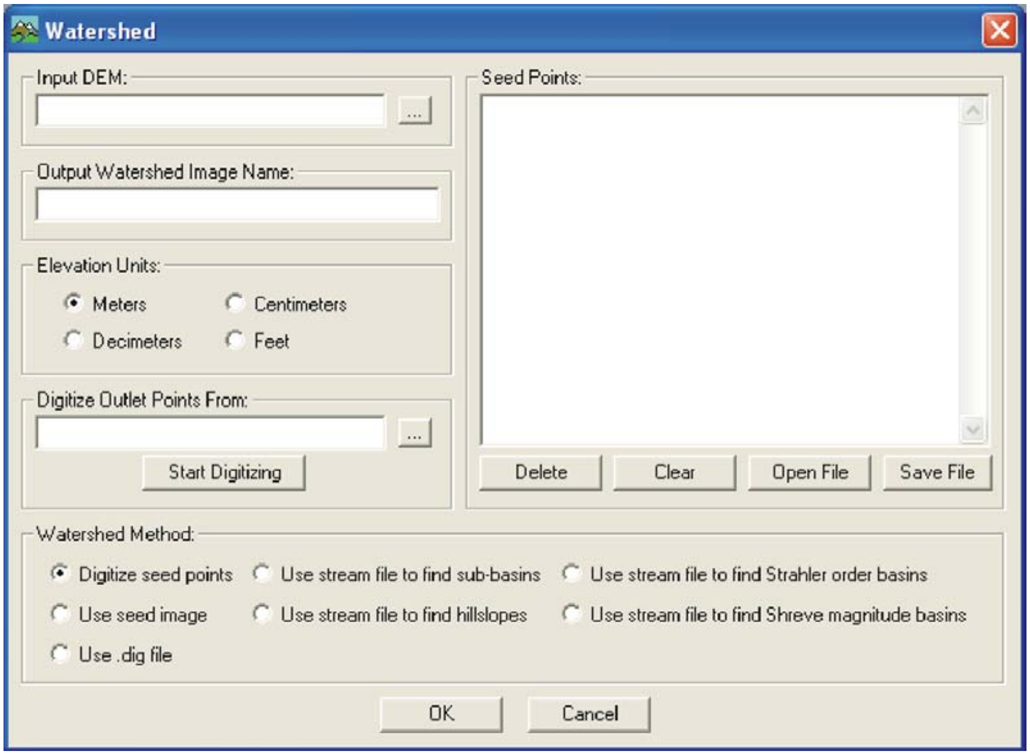
Q5. How would the derived stream network change if you raised or lowered the specified SCA threshold value? (2 marks)

Q6. Comment on the appropriateness of using a ‘minimum stream length’ in terms of the theory of channel initiation described in the opening of this section of the lab. How would the derived stream network have been different had you of selected a larger or smaller value for the minimum stream length? (3 marks)

iv. Delineating Watersheds

The SCA data layer told us the size of the catchment for all points in a DEM. However, sometimes we are more interested in delineating the watershed boundaries for a particular point than in simply knowing the catchment area.

1. Click *Terrain Analysis* menu ➔ *Primary Terrain Attributes* sub-menu ➔ *Extended Neighborhood* ➔ *Watershed*, or click the icon. The *Watershed* sub-program is launched.



Watershed

Input DEM:

Output Watershed Image Name:

Elevation Units:
● Meters ○ Centimeters
○ Decimeters ○ Feet

Digitize Outlet Points From:

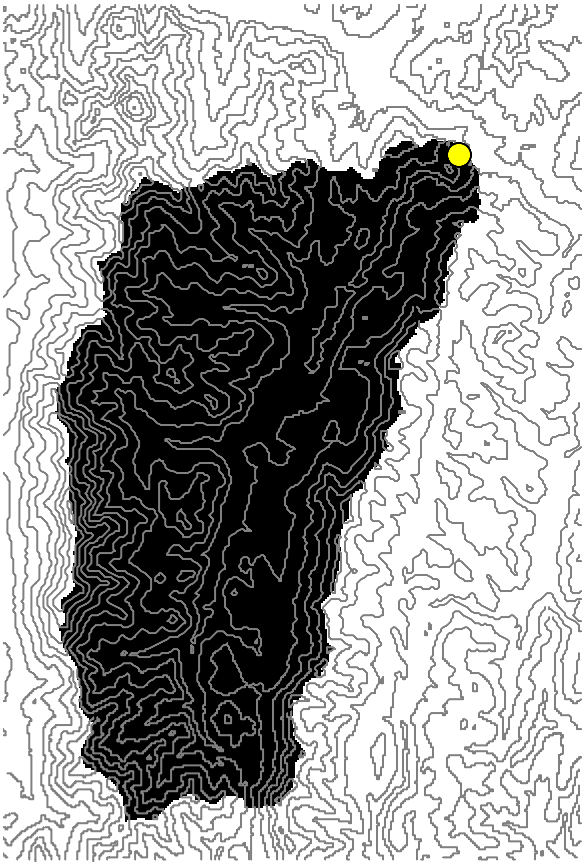
Seed Points:

Watershed Method:
● Digitize seed points ○ Use stream file to find sub-basins ○ Use stream file to find Strahler order basins
○ Use seed image ○ Use stream file to find hillslopes ○ Use stream file to find Shreve magnitude basins
○ Use .dig file

2. Select ‘Vermont Breached’ as the input DEM and call the output file ‘Vermont Watershed’.
3. Select ‘Vermont Breached_SCA’ for the ‘Digitize Outlet Points From’ textbox. Press the ‘Start Digitizing’ button. ‘Vermont Breached_SCA’ will be displayed in the default palette. Change the palette to ‘blueyellow’ using the *Image Attributes* toolbar.
4. Overlay the vector file ‘weir’ using the ‘mono_red’ palette and a point size of 2. This vector point shows the location of a weir where stream discharge is measured and recorded. We wish to delineate the watershed for this point. We could type the coordinates of this weir directly into the *Seed Points* textbox. However, if the weir coordinates are not exactly coincident with the digital stream, the resulting watershed

will be much smaller than expected. This is likely to occur even if the weir coordinates fall off the stream by a single cell.

5. Zoom into the area of the weir point. You will notice that the weir point does not fall on the line of high SCA values (i.e. the stream); it is out by about two cells. Place your cursor over the closest cell with high SCA value to the weir. Ensure that you are near the middle of the cell and click the left mouse button once. A large red circle should appear on the image centred on your chosen cell. You should also find that the coordinates of the point that you just digitized appeared in the *Seed Points* textbox of the *Watershed* window. If you had digitized multiple points, the program would find each watershed and assign a unique identifier to each. We will, however, only delineate this one watershed.
6. Close the open SCA image and press OK on the *Watershed* window. The program will calculate a D8 pointer file to identify all cells in the DEM that are connected to the weir cell. When the program has finished, open the image 'Vermont Watershed' using the 'BW' palette. Overlay the 'Vermont Contours' using the 'mono_gray' palette and a line size of 1. Now overlay the weir point (point size of 3). If you have done everything correctly, your image should look like the one below.

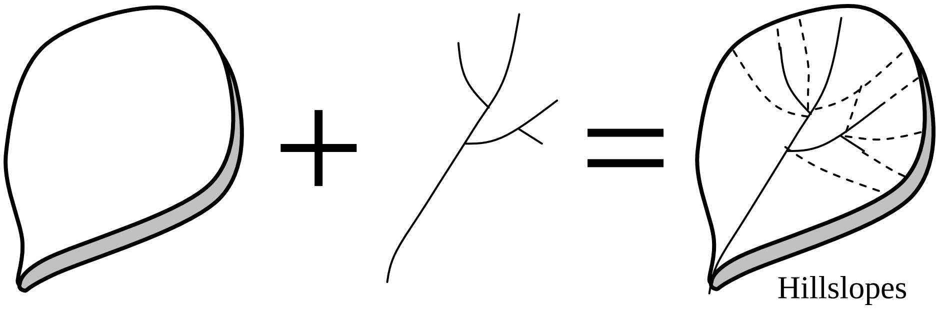


Notice that the watershed cells have been assigned the unique identifier of '1' (i.e., it was the first seed point in a list of one) and all points outside the watershed have values of '0'.

Q7. Before watersheds were delineated automatically using computers they were drawn by hand on contour maps. Perhaps you've done this in an introductory geography class. What are some advantages and disadvantages of the automated method? (6 marks)

v. Delineating Hillslopes

A hillslope is the area draining to one side of a reach (i.e. a section of a stream). Hillslopes are sometimes used in hydrological/ecological modeling to dissect landscapes.



1. Using the Raster calculator to multiply the images ‘Vermont Watershed’ and ‘Vermont Streams’. Because the watershed has values of ‘0’ and ‘1’, the resulting image will yield only those streams cells inside the watershed that you have delineated. Call the resulting image ‘Streams in Watershed’. Display the image to confirm that this has worked
2. Open the *Watershed* sub-program. Select ‘Vermont Breached’ as the input DEM and call the output file ‘Vermont Hillslopes’.
3. Choose the ‘Use streams to find hillslopes’ option and select ‘Streams in Watershed’ as the input stream image.
4. Press OK to run the program. TAS will assign a unique identifier to each stream reach and find the areas draining to them.
5. When the program has finished, display the resulting image using the ‘qualitative’ palette.
6. If you have not already done so in section iii, create a vector coverage of the streams to overlay on the hillslopes image by using the *Convert Streams to Vector* sub-program in the *Stream Network* sub-menu. The background value should be zero. Overlay the resulting vector stream file on the ‘Vermont Hillslopes’ image using the ‘mono_black’ palette and a line width of 2.

Q8. How many hillslopes are there in this watershed? How would this number have changed is we had chosen a smaller or larger SCA threshold for extracting the stream network in section iii? (2 marks)