Lab 4: Hydrological Analysis of Watersheds

Topics Covered in this Lab:

i. Flow routing algorithms
ii. Distributions of soil moisture and sediment transport potential
iii. Modelling mass fluxes

Take Home from Lab 4:

After completing this lab you will be familiar with some most commonly used flow routing algorithms, some useful terrain indices with hydrologic and geomorphic significance, and some basic modelling techniques.

You will need to copy the contents of the ‘Lab 4’ folder on the course directory.

Introduction:

It should be evident from Lab 2 that the drainage network derived from the D8 flow routing algorithm has a great deal of potential for modelling surface water hydrology and related phenomena in watersheds. Much of this work is based on the assumption that the discharge of water and sediment from a particular location is directly related to its catchment area. This is a fairly reasonable assumption in most watersheds. Combining information about the topological linking between grid cells and other terrain attributes (e.g., slope and aspect) allows for the computation of indices that describe the potential for soil saturation and erosion from overland flow. Additional information about land cover and climatic variables allows the terrain analyst to model the transport of water, sediment, and chemicals.

In this lab, we will use a DEM and land cover data for a coastal watershed called the Silly Salmon Creek watershed. Start by displaying the TAS composition file called ‘Silly Salmon Creek Map’ to get an appreciation for the landscape.

i. Flow Routing Algorithms

You were introduced to the most simplistic flow routing algorithm, D8, in Lab 2. In fact, there are many flow routing algorithms available and each algorithm results in slightly different drainage network. Because the drainage network is fundamental to the modelling of surface water hydrology, it is important to become familiar with commonly used routing methods. It can be difficult to decide when or where it is appropriate to use a particular routing algorithm. In this section of the lab, we will compare the output of four flow routing algorithms, including: D8, FD8 (Freeman, 1991; Quinn et al. 1991), D-infinity (Tarboton, 1998), and the Quinn et al. (1995) modification of FD8.

Routing algorithms differ in the way that they:

1. calculate flow direction;
2. model flow divergence, i.e., partition flow between neighbouring downslope cells;
3. handle streams.

D8 is incapable of modelling flow divergence (or dispersion) because of the flow from a particular grid cell is directed to a single downslope neighbour. FD8 (i.e., fractional D8) will divide flow to each downslope neighbour using a partitioning scheme that is based on the slopes to neighbours. D-infinity can divide flow between a maximum of two downslope neighbours based on the direction of maximum downward slope. Like FD8, the Quinn et al. (1995) modification of FD8 also partitions flow to each downslope neighbour, but it increases the degree of flow convergence from the catchment divide to the channel head. Thus, FD8-Quinn (1995) is the only algorithm of the four that explicitly recognizes that flow on hillslopes should be divergent while flow along valley bottoms should be convergent.

Let’s compare the patterns of SCA derived from each of these flow routing algorithms.

1. Open flow routing algorithms window in TAS by selecting the Terrain Analysis menu ➔ Primary Terrain Attributes sub-menu ➔ Extended Neighbourhoods sub-menu ➔ Catchment Area, or by selecting the ◆ icon. You will run this program four times: once to calculate the D8 SCA, once for the D-infinity SCA, once for the FD8 SCA, and once for the FD8-Quinn (1995) SCA. We will set the p value for FD8 and FD8-Quinn (1995) to 1.1, as suggested by Freeman (1991). Keep the CIT (i.e., channel initiation threshold) at 100,000 m^2 for FD8-Quinn (1995). This value determines the size of the catchment area needed before a stream starts, just like in Lab 2 when we set a threshold value to extract streams. Because we want to compare the visual pattern of SCA derived by each of these algorithms, we will **check the Ln(catchment area) box** (refer to Lab 2 for why we do this).

2. Use ‘Silly Salmon Creek DEM’ as your input DEM. The output names will automatically assigned by TAS and will consist of the DEM name, the flow algorithm used, and ‘SCA’.
3. Open ‘Silly Salmon Creek DEM_D8SCA’ and ‘Silly Salmon Creek DEM_FD8SCA’ using the ‘blueyellow’ palette.

Q1. Which of the two SCA images has more grid cells with the lowest SCA value of 3.4 (represented by black in the ‘blueyellow’ palette)? These grid cells have no inflowing links in their corresponding drainage networks. In actuality, this condition should only occur at drainage divides. Based on what you know about the D8 and FD8 routing algorithms, why do you think this difference exists? (3 marks)

Q2. Flow divergence is apparent in SCA images by a fuzzy quality, almost like the SCA has been smudged. Zoom into corresponding parts of the D8 and FD8 SCA images. Comment on each algorithm’s ability to represent divergent flow on hillslopes and convergent flow in stream channels. That is, which algorithm is better in which part of the landscape and why? (4 marks)

Q3. How does the D-infinity SCA image compare with the D8 and FD8 images in terms of (1) the number of low values, (2) flow divergence on hillslopes, and (3) flow convergence along valley bottoms? (3 marks)

Q4. How does the FD8-Quinn (1995) SCA image compare with the D8, FD8, and D-infinity SCA images in terms of (1) the number of low values, (2) flow divergence on hillslopes, and (3) flow convergence along valley bottoms? (3 marks)

Q5. Which algorithm performed best in this landscape and why? Suggest a landscape type where this may not be the case. (3 marks)

ii. Distribution of Soil Moisture and Sediment Transport Potential

Surface water runoff is generated from locations of soil saturation in a watershed. Soil saturation is related to surface topography and a number of soil properties (e.g., soil depth, composition, etc.). Although the distribution of soil properties within a watershed can be difficult to characterize accurately, the affect of topography on the likelihood for soil saturation can be modelled using the *wetness index* (sometimes called the catenary index; Beven and Kirkby, 1979). The wetness index is defined as:

$$WI = \ln\left(\frac{SCA}{\tan\beta}\right)$$

where:

WI	wetness index
SCA	specific catchment area
ln	natural logarithm
tan	tangent function
β	local slope in degrees

1. Open the ‘Secondary Terrain Attributes’ window by selecting Terrain Attributes menu ➔ Compound Terrain Attributes sub-menu ➔ Wetness Index or by clicking the icon.
2. Choose ‘Silly Salmon Creek DEM’ as your input DEM. Check the boxes for the Wetness Index and the Relative Stream Power Index. (We generate the RSP index for later use)
3. Select the FD8-Quinn (1995) flow algorithm. Set the p value to 1.1 and keep the default CIT value of 100,000. Press OK.
4. Display the image ‘Silly Salmon Creek DEM_WI’ in the ‘blueyellow’ palette. It should be clear by examining the equation for WI, that as local slope approaches zero, WI becomes very large. Your WI image likely has some very large values (999999) corresponding to the flat ocean area in the image. Change the display maximum on the Image Attributes toolbar to something more reasonable like 10.
5. Overlay the vector file ‘Silly Salmon Creek DEM Contours’ using the ‘mono_white’ palette. Zoom into the image and move around to get an appreciation for the distribution of WI values.

Q6. It should be evident to you that valley bottoms and flat areas have the highest values of WI in the landscape. Comment on the distribution of WI on the hillslopes. What types of hillslopes are more likely to be saturated? (hint: what is the relation between the contours and WI in hillslope areas?) (2 marks)

Q7. Surface water runoff flows through a watershed far faster than water that infiltrates into the soil and travels as shallow or deep groundwater. Therefore, surface water runoff is usually the first to reach a watershed outlet after a heavy rainstorm. Silly Salmon Creek has two main branches, the south branch (with the reservoir, see 'Silly Salmon Creek Map') and the north branch. Considering the values of WI, which of the two branches of Silly Salmon Creek do you thing contributes more surface water runoff and why? (2 marks)

The *relative stream power index* is a measure of the erosive power of flowing water. It has been used extensively in studies of erosion and sediment transport. Relative stream power (RSP) is calculated as:

$$RSP = SCA \tan \beta$$

6. Display the image 'Silly Salmon Creek DEM_RSP' in the 'blueyellow' palette with a maximum value of 200. Zoom into the image and move around to get an appreciation of the distribution of values of RSP.

Q8. Referring to the equation for RSP, why do you think that valley bottoms demonstrate discontinuously high RSP values? (1 mark)

7. Overlay the vector file 'Reservoir' using the 'mono_blue' palette (fill the polygon). Zoom into the area around the Silly Salmon Reservoir. Notice that the outlet to the reservoir is on the western side of the lake.

Q9. The Silly Salmon Reservoir is filling in with sediment quicker than the engineers who built it had anticipated. Local authorities would like to put measures in place to prolong the life of their reservoir but have limited funds to do so. Based on the RSP values of the catchment area draining into Silly Salmon Reservoir, do you think that they should concentrate their efforts in the catchments draining to the northern, eastern or southern shores of the reservoir? Why do you think so? (3 marks)

iii. Modelling Mass Fluxes

A major highway was built through Silly Salmon watershed a year ago (see Silly Salmon Creek map). Local fishers are concerned that the cuts and fills made during the road construction will increase the amount of sediment in waterways and deteriorate salmon spawning grounds. We will model the transfer of sediment from the road to waterways using our knowledge of the drainage network and land cover, using TAS's Mass Accumulation program. The Mass Accumulation program works very much like the algorithms that calculate SCA; however, instead of calculating the area upslope of a cell, Mass Accumulation calculates the upslope load that passes through the cell, taking into account losses due to the efficiency of the load transfer. If it isn't clear to you how this works, perhaps it would be better to see it in action.

1. Open the Mass Accumulation sub-program by selecting Terrain Analysis menu ➔ Compound Terrain Attributes sub-menu ➔ Mass Accumulation. This program is used to model the spatial pattern of mass (i.e., water, sediment, or nutrients) flux in a watershed. The loading image represents the source of the mass to be accumulated. In our case this load is the sediment associated with the road.
2. Display the image 'loading'. You should find that it contains mostly zero values with some cells containing the value 4.5. This value represents an average load of 15 kilograms of sediment per 100 m of road, which is our estimate of how much sediment the road construction created.
3. Display the image 'efficiency' using the 'quant' palette. This image describes the percentage of the mass that enters a cell is able to pass through, and how much is lost (i.e., deposited). In our example of sediment transport, the efficiency is largely determined by local slope and land cover (e.g. streams, roads, vegetation). Steeper slopes allow for greater sediment transport and less deposition. Similarly, some land covers allow for greater sediment transport than others.
4. Specify 'Silly Salmon Creek DEM' as your input DEM. The loading and efficiency images are appropriately named 'loading' and 'efficiency'. The DEM units are in meters. We will run this program three times, using each of the available flow routing algorithms, to compare the effects of each. Call your output images 'sediment transfer D8', 'sediment transfer Dinf', and 'sediment transfer FD8'. Use the default p-value for the FD8 algorithm.
5. Open each of the resulting images using the 'quant' palette. Use a common maximum Z value for each of 330.

Q10. Which simulation resulted in the lowest sediment transfers to Silly Salmon Creek and which resulted in the highest? Explain the differences between the three simulations. (hint consider how each of the three flow routing algorithms differ and the efficiency image) (4 marks)

Q11. Examine ‘sediment transfer Dinf’. Which two locations experience the greatest impact from the road construction? What does this mean in terms of managing this problem? (3 marks)

Q12. Does the entire road contribute sediment to local waterways? Where should we concentrate efforts to trap sediment before it enters the stream? (2 marks)

Q13. Suggest another environmental problem/phenomenon that could be modelled using the Mass Accumulation program. (2 marks)