Earth Surface Processes and Landscape Evolution
Topographic analysis using ArcGIS

The objectives of this practical are:

- To learn how to get hold of DEM data for mountainous regions (or anywhere else!). We will investigate the Andes in this practical.
- To calculate derivatives of the topography, such as slope, ready for further analysis.
- To isolate an area for analysis.
- To calculate drainage density and consider how this varies across the Andes.

Background: what can DEMs tell us?

Digital elevation data are available pretty much globally, and at a range of spatial resolutions. They provide us with quantitative information about the elevation, and therefore shape, of the land surface. This data can therefore be analysed to understand its characteristics so that it can be related back to the processes that influenced the topographic evolution of a region.

In the case of understanding orogens and their interactions with erosion, there are a number of key characteristics which can provide the basis for such an analysis:

River profiles are a very common and powerful tool for understanding landscape evolution and in particular the interplay between fluvial and glacial erosion and uplift. In these, you can often see how landscapes react to sudden changes in base level (creating knickpoints), and whether sections of the profile are overdeepened (e.g. by glaciers). You can also identify whether a river is in equilibrium with any uplift in that an equilibrium profile should start steep and gradually flatten out (i.e. it would be a nice concave 'graded' profile).

Drainage density is a measurement of the total length of rivers within a catchment normalised per unit area of the catchment. Thus you can see that as different process act to erode the landscape you might see a re-organisation of drainage density.

Instructions

We will use several techniques that you have seen in the lectures and practicals, but will also apply many new techniques. Please refer to your lecture notes as you work through today's practical. Remember that ArcGIS tools all have *Tool Help* and that more detailed *Help Documentation* is also available, so get used to using these to understand how to use tools and carry out analyses.

Dataset: Shuttle Radar Topography Mission (SRTM) DEM

The data we will use are from a global elevation dataset based on data collected by the Shuttle Radar Topography Mission in 2000. The data are on the web at: http://www.opentopography.org and consist of a collection of 1 and 3 arc second resolution DEMs organised by region. 1 arc-second equates to approximately 30 m resolution, and 3-arc seconds is ca. 90 m resolution. Note that because we are obtaining data from a global dataset, it is in a 'projection' that is applicable to the whole globe. This causes a problem because the units of distance measurement in such projections are decimal degrees as opposed to meters, which are much more useful for measuring landscape elements. Therefore, we often have to project the data into a new projection which is applicable to our more local region of interest so that measurements can be done in meters.

1. Explore the Andes using Google Earth

Use Google Earth to have a look at the north, central and southern Andes in turn. Looking at a few catchments in each area, make some notes (in the box on the next page) on how you would describe the geomorphological differences between these landscapes, in particular thinking about whether you can say anything about the patterns of erosion (or deposition) and the shapes of the mountains.

Northern Andes:

Mid-Andes

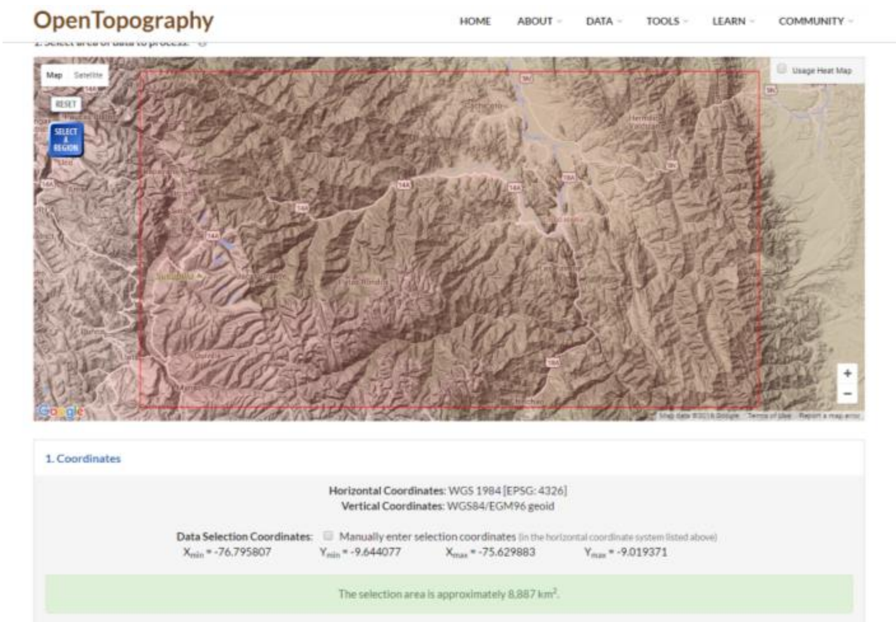
Southern Andes

The point is that qualitative observations can only get you so far in terms of identifying interactions between mountains and erosion. You can't be terribly certain what processes you are identifying. We therefore need to quantitatively analyse some digital elevation model (DEM) data.

2. Getting DEM data for mountainous (and other) regions

Go to the OpenTopography website (www.opentopography.org). We are going to download data for small parts of South America as there is too much data to deal with the whole mountain range in a single practical.

- Click the *Data* menu and use the map to *select a region* that you wish to download (zoom in and then press the 'Select a Region' button). Each of you should download mountain DEMs for a different area (north, central or southern Andes). Try something on the order of the scale I am showing below – i.e., a band of topography that extends across the Andes from west to east that incorporates some obvious drainage basins. You can make it as extensive north to south as you wish, but I wouldn't go too far otherwise the data download will be huge.

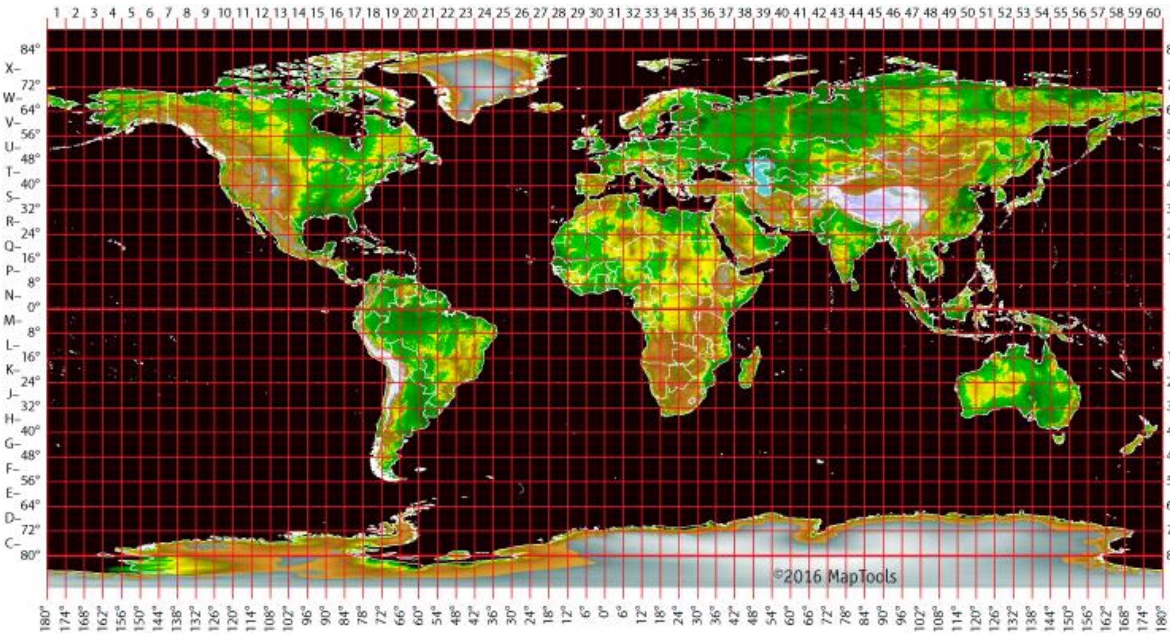


- Once you've highlighted an area, scroll down and look at the datasets listed against 'Shuttle Radar Topography Mission (SRTM) Global'. Select SRTM GL1 for 30 m resolution data or SRTM GL3 for 90 m resolution data. The choice is up to you, but **I recommend that for speed, you use the 90 m data today**! Note, however, that the same approaches described here can be used for 30 m data for other purposes.
- *Submit* the job and let Open Topography generate your *job results* before downloading and saving the .gz file. Use 7-zip to extract the contents of the .gz file to a space on your network drive. Open ArcGIS and add the .tif to your map.

You now need to convert the projection of your DEM section into a spatial reference that uses meters rather than decimal degrees:

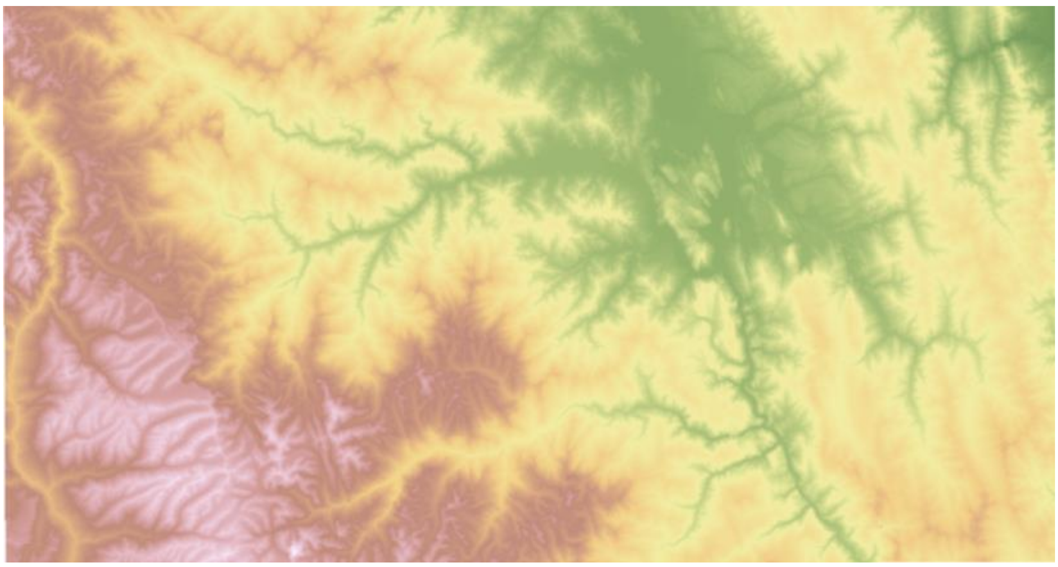
- Go to: ArcToolbox → *Data Management Tools* → *Projections and Transformations* → *Raster* → *Project Raster.* The *Input Raster* should be your small DEM. The *Output*

Coordinate System should be*: Projected Coordinate Systems → UTM →WGS 1984 →Southern Hemisphere → SELECT A UTM ZONE* (use the map below to identify which UTM zone you should be in for your particular area). Press *OK* to make the tool run and add the projected dataset to your map.



Map showing UTM Zones. E.g. Ireland is in UTM Zone 29N, and the South Island of New Zealand is mostly in UTM Zone 59S.

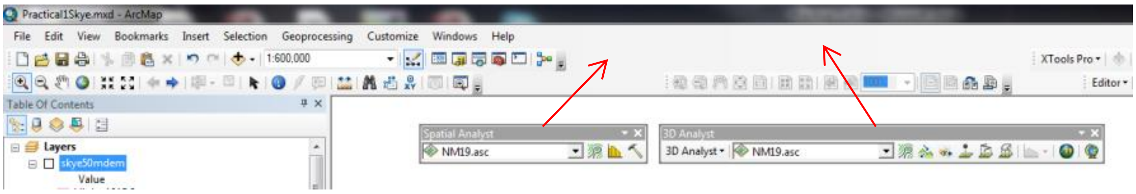
You should now have a dataset that is ready for analysis. **You should use this properly projected DEM data from now on!** I show mine below:



3. Switching on 'Spatial Analyst' and '3D Analyst'

Most raster processing, and especially morphometric analysis, in ArcGIS is carried out by an 'extension' called **Spatial Analyst**. In addition, some analysis tools are provided by the additional extension called **3D Analyst**. The extensions consist of toolbars and toolboxes and they need to be enabled before they can be used. If the *Spatial Analyst* and *3D Analyst* toolbars and toolboxes are not visible then carry out the steps in the next 3 points:

- Enable the extensions: *Customize* → *Extensions…* → select *3d Analyst* and *Spatial Analyst* → *Close*.
- Add the toolbars: *Customize* → *Toolbars* → select *3d Analyst* and *Spatial Analyst*.
- Drag the toolbars to wherever you want them:



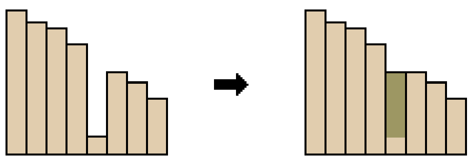
We are now ready to clean-up our dataset prior to analysis

4. Delineating Drainage

We are now going to delineate drainage catchment boundaries and rivers in the area so that we can narrow down our analysis window and apply some morphometric techniques to understand the shape of the landscape and therefore hopefully to understand some of the processes that created the landscape. There are multiple stages to delineating drainage, all of which require the *Spatial Analyst Tools* part of *ArcToolbox*.

Drainage analysis using a DEM has several steps. First, the DEM must have any internal 'pits' filled to create a version of the DEM that allows water to flow properly over its surface to reach the sea (or the edges of the raster). Second, the GIS has to calculate the direction any water would flow over the 'filled' DEM. Third, the GIS then needs to use the direction raster to calculate how many pixels in the DEM would flow into one another (this is called a flow accumulation). Using the flow accumulation, the GIS can then calculate the lines which would represent river flow, and it can calculate the outline of a drainage basin. We will go through each of these stages below.

4.1. Pit Filling



In many DEMs, there will be areas which, if one were to try and calculate water flow, would collect water but would not then allow it to flow out. An example would be a topographic basin. Although these features may be real, for drainage calculations we must 'fill' them so that water can escape from these 'pits' and continue flowing (see figure). Let's *fill* the DEM:

- Go to *Spatial Analyst* → *Hydrology* → *Fill*. Insert details of your *Input Raster* (your zoomed in DEM), and the name of an *Output Raster* you want to create (e.g. *AndesNorthFill.tif*). Ignore the Z-limit (but read the help on what it is if you like!). Press *OK* to carry out the filling of the DEM.
- Note that the GIS may take considerable time to do this 'Filling' (possibly up to several minutes depending on the machine and the size of the raster).

You should now have a DEM that doesn't look much different from the one you already had, but which is ready to be used for the remaining hydrological analysis. Don't use the original DEM for the steps that follow or you will generate a number of error messages!

4.2. Flow Direction

Now that we have a pit-filled DEM we can calculate the direction which water would flow if it were to rain on that part of the Andes. This 'flow direction' raster will then enable the GIS to calculate the remaining hydrological components of interest. To calculate flow direction:

- Go to *Spatial Analyst Tools* → *Hydrology* → *Flow Direction*.
- Run the tool using the filled DEM you just made as the *Input surface raster* and give your *output raster* a sensible name (in my case I am calling it AndesNorthFillFlowDir.tif). Ignore the 'Drop Raster' but do put a tick in the 'Force all edge cells to flow outward' as this latter option can help when trying to delineate rivers.

32	64	128
16		1
8	4	2

You should now have a new raster which looks rather odd and has values of 1,2,4,8,16,32,64 or 128. Each value corresponds to the possible directions water could flow out of an individual cell in the DEM. The figure on the right shows what the numbers represent in terms of water flowing from the blue central cell/pixel. In the flow direction raster, the value given to the pixel represents the steepest direction of flow from that cell. So, a pixel has a value of 64 then you know the steepest path for water to flow down and out of the pixel would be to go in the top center direction. ArcGIS uses that information to do the next steps in hydrological calculations: the flow accumulation, and the calculation of drainage basin outlines.

4.3. Flow Accumulation

Flow accumulation is a simple calculation that uses the flow direction raster to count how many cells/pixels are upstream of any particular pixel (think 'upstream area' or 'upstream contributing area' – as mentioned in many E&O papers!). This is effectively a calculation to find out how water would flow downhill and accumulate in flows that are big enough to become rivers. If we know the patterns of river flow then we can analyse various things including drainage density and river profiles. To calculate flow accumulation:

- Go to *Spatial Analyst Tools* → *Hydrology* → *Flow Accumulation*.
- Fill in all the information, giving the flow direction raster as an input, and giving a sensible output name. Ignore the *Input weight Raster* as you do not need this, and set the *Output data type* to be *INTEGER*. Click *OK* to run the tool.

You should be presented with a new raster that looks pretty much all black apart from a few areas which look like white or grey rivers. We can now convert this flow accumulation data to delineate where the rivers flow…

4.4. Rivers

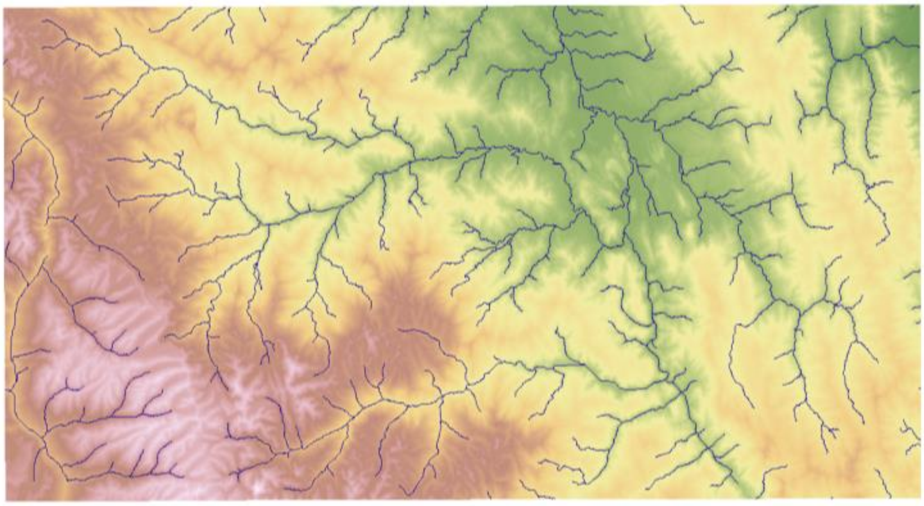
In reality, a river is defined by how much water can be collected so that continuous flow can occur. As the river flows downstream, it tends to capture more water and becomes bigger. This sort of information is *exactly* what is contained in the *flow accumulation* raster that you just made. Thus all we need to do to make the map of rivers stand out more clearly is to decide on a threshold for the number of cells (i.e., the minimum upstream area) that would accumulate to cause a river to start flowing. Here, because we just want to understand the broad scale river systems in the Andes, we can set an area threshold to be quite high (e.g., 5000 cells – equivalent to an area of ca. 40 km^2 in a ca. 90 m resolution raster). We can tell ArcGIS to set everywhere in the flow accumulation raster to be null (a special value in raster processing) unless flow accumulation is greater than or equal to 5000, and otherwise to give the new raster a value of 1. Let's delineate the rivers:

- Go to *ArcToolbox* → *Spatial Analyst Tools* → *Conditional* → *Set Null.*
- Enter your flow accumulation dataset as the *Input conditional raster*, and then, in *expression* type ***VALUE < 5000***. For the *input false raster or constant value*, give it a value of ***1***. Provide a sensible name for your *output raster*. Press *OK* once all the boxes are filled.

This set null process will look at your flow accumulation dataset and, if there is not enough flow (that is, less than 5,000 cells) to form a river then it will give the new dataset a value of *null* (also known as *NoData*). Otherwise, if there is enough accumulating flow then the new dataset will have a value of 1. The output, therefore, will be a dataset where all 'river' cells will have a value of 1, and anywhere else will have no value.

- Now convert this raster to a shapefile using the *ArcToolbox* → *Conversion Tools* → *From Raster* → *Raster to Polyline* tool. Choices to make should be obvious, but make sure you select *Background Value* to be *NODATA* and tell the tool NOT to *Simplify polylines*. Ignore the dangle length.

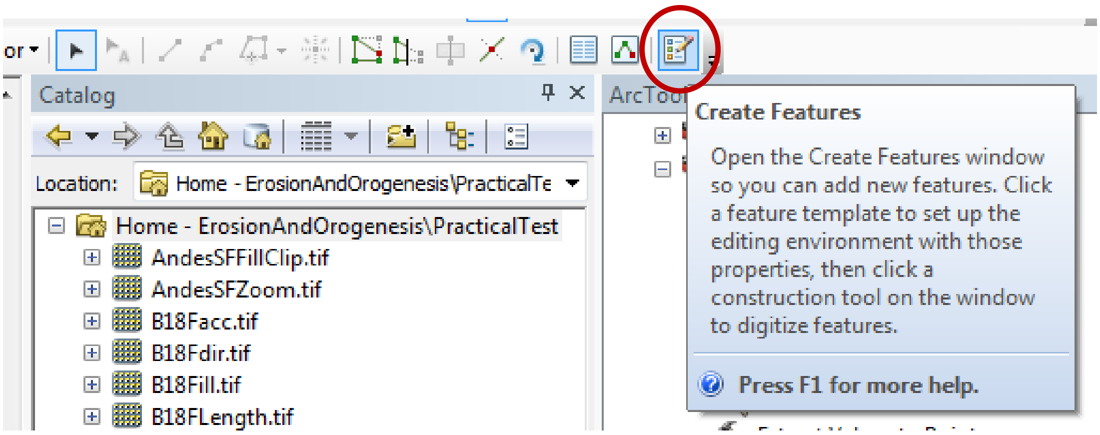
Hopefully you now have a map of what the rivers in your study region look like. Mine is below with rivers shown as blue lines:



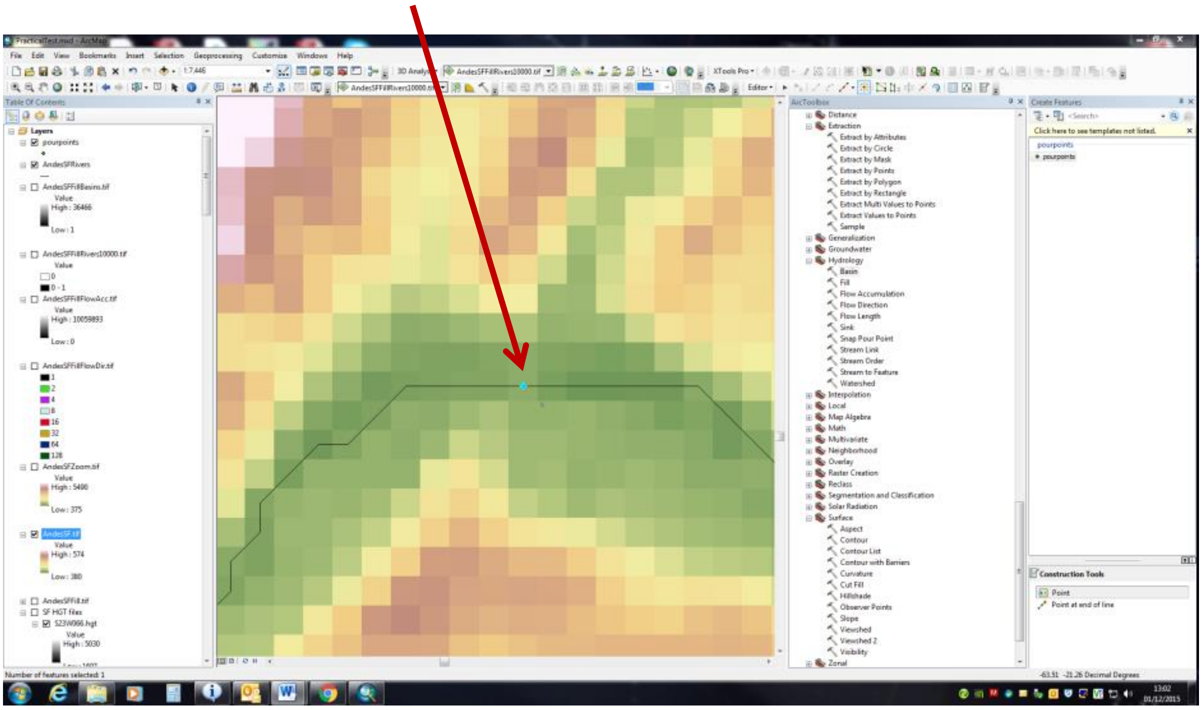
4.5. Drainage Basins (Catchments)

A sensible and easily definable areal unit of analysis is the drainage basin. We can use the *Flow Direction* raster again as an input to another tool which can identify drainage basins/catchments. There are actually two ways to do this, one which delineates ALL catchments, but which can produce spurious results, and one which delineates only those catchments you tell it to. We will do the latter and delineate a single catchment that drains through a single 'pour point'.

- Use *ArcCatalog* to create a new point shapefile called *pourpoints.shp* in your folder (*right-click on the folder* → *New* → *Shapefile* and then fill in the appropriate details including editing the spatial reference so that it is the same as your projected DEM.
- Use the Editor toolbar to *Start editing* for that shapefile. Press the *Create features* button on the *Editor toolbar* so that you can see some construction tools related to your shapefile:



- Now, make sure your rivers shapefile is switched on and zoom (quite close in so that you can see individual pixels in the underlying DEM) in to the end of the river where it leaves the drainage catchment of interest. Select the *Point* construction tool and then *click on the location you want to represent the 'pour point' at the end of your catchment* – a new point should be added – like this:



- Go to the *Editor toolbar* and *stop Editing* saving this 'pour point' shapefile if asked.

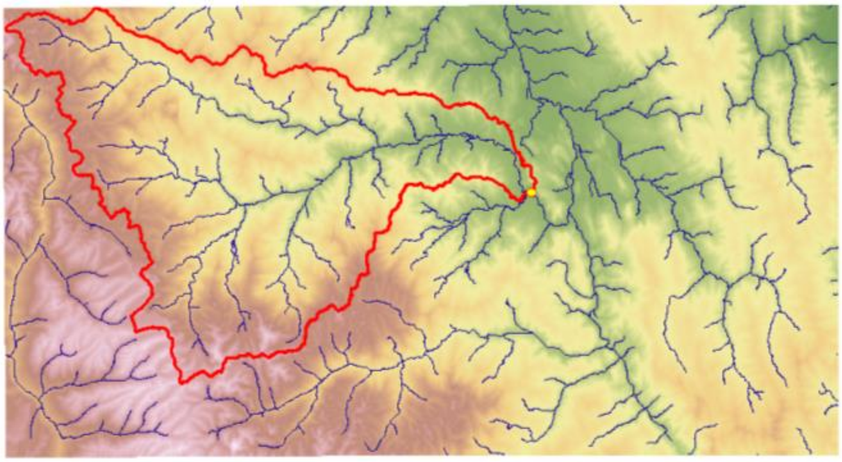
Now we can derive the catchment. This involves outlining the whole area upstream of the pour point that you just defined:

- Go to *Spatial Analyst Tools* → *Hydrology* → *Watershed* and run the tool using your flow direction raster and your pour point shapefile as inputs.

In the raster that this produces, you will have a black area representing your basin. We need to convert that to a polygon shapefile so that we can use it as a cookie-cutter to analyse the landscape ONLY in that catchment:

- *ArcToolbox* → *Conversion Tools* → *From Raster* → *Raster to Polygon*. Make sure that the *Simplify polygons* box is **NOT** checked. Press *OK* once you have filled in the tool.

You should end up with something like this but for your area:



Now we can use this catchment as the basis for further analysis including doing a stream profile and looking at hypsometry, slope distribution and drainage density.

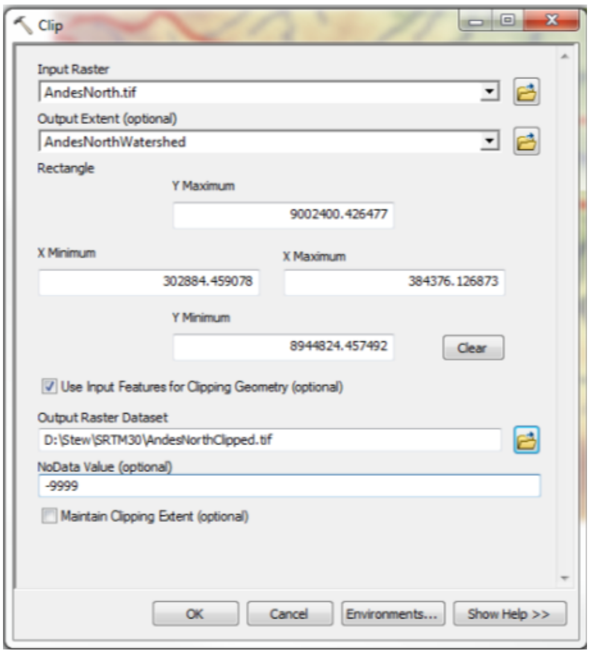
- Use the "Identify" tool to click on your pourpoint and find the coordinates (UTM Northing and Easting). Add them into the group spreadsheet under the correct heading (Northern, Central, or Southern Andes). We will update this as we go along with data on the slope and drainage density of your basin. You can find the spreadsheet using this link:

https://durhamuniversity-my.sharepoint.com/:x:/g/personal/bjdd72_durham_ac_uk/EXHi5uKsWRdNrNR4Zhbroj4Bkc9TgBDGdu0Uz9BF6WFRyw?e=wA9Jhk

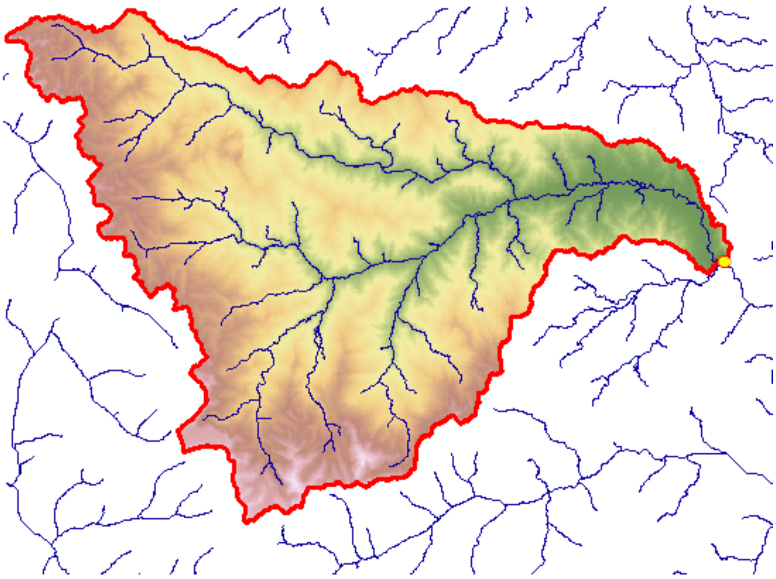
5. Clipping to a particular basin

For many analyses, you would normally be interested in looking at a particular basin. Let's clip the DEM to only include the catchment of interest:

- *ArcToolbox* → *Data Management Tools* → *Raster* → *Raster Processing* → *Clip*: enter your *Input raster* (our original DEM) and your *Output extent* (your catchment from step 4.5), put a check in the *Use Input Features for Clipping Geometry* box, choose a sensible *output raster dataset* name, and enter a *NoData* value of *-9999*. Make sure *Maintain Clipping Extent* is **not** checked. My choices are shown below. Press *OK*.



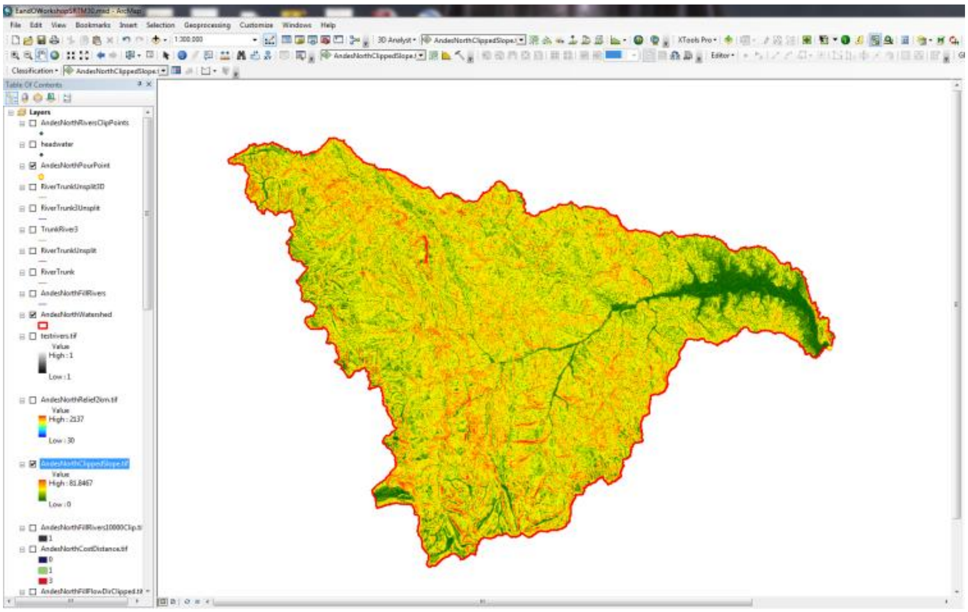
You should end up with a DEM which is 'clipped' to the extent of your drainage catchment/basin.



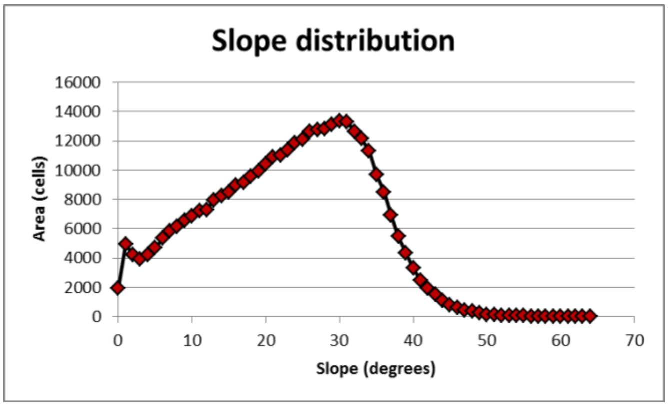
6. Calculating slope distributions

Calculating slope is very easy in ArcGIS:

- Go to *ArcToolbox* → *Spatial Analyst Tools* → *Surface* → *Slope.* Tell the Slope tool to calculate slope in *degrees* across the version of the DEM which is clipped to the catchment extent. Press *OK* to calculate slope.



- Convert this to an *integer* dataset (this will allow us access to the table of data we need): *ArcToolbox → Spatial Analyst Tools → Math → Int.*
- Now open the Attribute table for this new integer version of your DEM. On the table, click on the Table Options button, and then Export. Select to export a .txt file (which we can then open in Excel). If prompted, **don't add** the table to the map document.
- Open your slope file in Excel (note: you need to tell Excel to look for ***All files***, and then tell Excel that it's a *Delimited* file and that it is *Comma* delimited).
- Plot the Value (slope) vs. Count (area) columns as a scatter plot. Mine looks like this. **Note that this is a slope distribution and NOT a slope-area (slope vs. drainage area) or a slope-elevation plot like we have seen in the lectures.** If you wish, you're free to make a plot of slope and area for each cell in the DEM, but that's beyond the scope of this workshop. Instead, this plot simply indicates whether particular slopes are more common in a landscape:



Discuss what your slope distribution histograms mean. Can you relate them to any processes? Or thresholds?

- **Calculate the mean slope for the watershed in Excel using the data from the Attribute Table. Add it to the class spreadsheet for your basin.**

7. Drainage Density

Drainage density is a measure of the cumulative length of the stream segments divided by the area of the drainage catchment. We might expect that this would vary depending on the processes that are active in the environment, because glaciers might re-organise drainage differently to fluvial landscapes, and likewise tectonically-active regions may have different drainage densities to more quiescent areas. We can calculate drainage density like this:

- Go to *ArcToolbox* → *Analysis Tools* → *Overlay* → *Intersect.* Add your watershed polygon and your river shapefile to be the inputs to the tool. The remainder of the tool should be self-explanatory. This is going to produce a dataset of rivers only for inside your watershed.
- We need to calculate the length of all the river segments in the catchment. Open the Attribute table of the *intersected rivers* dataset you created. Add a new Field and call it Length (make it of *Float* type). Right-click on the top of the *Length* column you just created and select *Calculate Geometry*. Choose *Length* and press *OK.*
- Now highlight the *Length* column and then right-click on the top of the length field and select Statistics. Jot down the 'Sum' of the river lengths.
- We now need to calculate the area of the watershed. Open the attribute Table of the watershed and add a new field for area. Calculate the Area geometry. Jot down the area of the watershed.
- Now divide the total length of the rivers by the drainage area of the watershed. **Be careful with units: make sure the area is in km^2 and the lengths are in km.**
- My area was 2,932.62 km^2 and my sum of river lengths was 1,031,282 m. Thus my drainage density is 0.35 km/km^2. Note that this value is completely dependent upon the cell threshold used to define rivers earlier (e.g., 5,000 cells). Thus these drainage density values can only be compared to other watersheds where an identical river threshold is used.

What is the drainage density for the area you have chosen? Add this to the group spreadsheet for your basin. We will compile this for the whole class and then use this to see if there are any detectable differences in drainage density between each region.

8. Compiling the data

Once everyone has input their data, COPY THE SPREADSHEET TO YOUR OWN COMPUTER SO YOU HAVE A LOCAL COPY. Make a scatter plot of drainage density vs. mean slope for the Northern, Central and Southern Andes.

- Is there any relationship between slope and drainage density? If so, what is it? (There might not be any relationship – this is the first time we've tried this, so I'm not sure what it will show!)

- Is there any difference in drainage density between the different regions of the Andes?

9. Summary

Today we have looked at a range of techniques aimed at quantifying and characterising topography. They are techniques that are commonly applied in studies that seek to understand Earth surface processes. There are many other techniques that one can apply. Check out the following websites for more information:

http://gis4geomorphology.com/ (A great source for how to do various analyses)

https://sites.google.com/site/sorsbysj/geospatial-processing (Instructions for analysing things using a different GIS called 'GRASS', but the explanations are relevant).

Extra analyses (might be useful for your project):

Stream profile analysis

Stream profiles can be generated by plotting the elevation of our DEM at positions along one of the rivers in our catchment:

- Turn off all the layers apart from the rivers shapefile. Use the *Select Features* button to select all the parts of a trunk stream that flows from the top of the mountains down to your pour point.
- When selecting, you will need to be zoomed in close to the shapefile to ensure you select all the tiny bits of the river, and also to ensure you do not select any little tributary streams by mistake. This can be fiddly with complicated river networks.
- Once your main trunk is all highlighted as being selected, right click on the rivers layer → *Data* → *Export Data*. Export the *selected* data to a new shapefile representing the main trunk of your river.
- Go to *ArcToolbox* → *Data Management Tools* → *Features* → *Unsplit Line* and then put your trunk river dataset in as the input, and select an appropriate place for the output. Press *OK* to run the tool.

You should now have a single line shapefile which represents your river – we can now extract a river profile!

- Open the *3D Analyst* → *Functional Surface* → *Interpolate Shape* tool
- Set the *Input Surface* to be the original Andes DEM, the *input feature class* to be the *river* you just created. Specify an output location / name and leave all other options as default. This will save a new 3D shapefile of your river.

- Use the selection button  to select the river in your 3D dataset (it should turn light blue).
- Add the *3D Analyst toolbar* to the display and make sure the corresponding extension is turned on.
- Make sure the original (not filled) DEM dataset is shown from the drop-down list on the 3D Analyst toolbar. Click the dropdown arrow at the end of the 3D analyst toolbar and select the *Profile Graph* tool to draw an elevation profile of your river.
- Export the graph to Excel if you like.